STRONTIUM
A MATERIALS SURVEY

BY ALBERT E. SCHRECK AND JOSEPH C. ARUNDALE

* * * * * * * * **Information Circular 7933**

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OFFICE OF THE DIRECTOR

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF MINES
WASHINGTON 25, D. C.

Hon. Leo A. Hoegh
Director
Office of Civil & Defense Mobilization
Washington 25, D. C.

Dear Mr. Hoegh:

Copies of the Materials Survey - Strontium, prepared by the Bureau of Mines for the Office of Civil and Defense Mobilization, are being forwarded to your office.

This report is the fifth Materials Survey to be completed or revised under the terms of the April 15, 1955 agreement between the Department of the Interior and the Office of Civil and Defense Mobilization which assigned responsibility to Interior for preparation and revision of Surveys covering 45 mineral commodities. A total of sixteen Materials Surveys has now been published by the Bureau of Mines, the first editions of twelve having been prepared under an agreement made in 1950 with the National Security Resources Board.

Manuscript revisions proposed by reviewing officials of the Office of Civil and Defense Mobilization have been incorporated in the Survey.

Sincerely yours,

Marling J. Ankeny
Director

Foreword

The Materials Survey series is being prepared under the sponsorship of the Office of Civil and Defense Mobilization to provide comprehensive fundamental information on materials essential to the National Security. This survey, concerning strontium, is one of many being prepared by the Bureau of Mines, Department of the Interior. A complete list of Materials Surveys prepared by the Bureau of Mines can be found at the end of the bibliography of this report.

Strontium in the form of various compounds is essential to the national defense, primarily for use in pyrotechnics, tracer bullets, and military signal and warning flares. Although the domestic reserve of strontium minerals totals millions of tons, nearly all of our mineral requirements is supplied from foreign sources. Strontium minerals are considered strategic and critical materials to be acquired for the national stockpile.

The report was prepared under the general direction of Charles W. Merrill, chief, Division of Minerals, Federal Bureau of Mines and under the direct supervision of G. W. Josephson, chief, Branch of Construction and Chemical Materials.

CHARLES W. MERRILL,
Chief, Division of Minerals.

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STRONTIUM[1]

A MATERIALS SURVEY

BY

ALBERT E. SCHRECK[2] AND JOSEPH C. ARUNDALE[3]

Introduction and Summary

THE COMPOUNDS of strontium were confused with those of barium until 1790, when A. Crawford discovered that the mineral strontianite, long believed to be a barium mineral, was a compound of a new element. This discovery was confirmed 2 years later by I. C. Hope. The mineral was named strontianite because it was found near the town of Strontian in Argyllshire, Scotland. In 1808 Sir Humphrey Davy isolated strontium metal by the electrolysis of fused chlorides.

Celestite (strontium sulfate) and strontianite (strontium carbonate) are the principal strontium minerals. Because of its more widespread occurrence, celestite is more important commercially.

The most important use for strontium minerals is as the basic raw material for manufacturing strontium compounds, and the bulk of the strontium consumed is in the form of these compounds.

Strontium compounds (primarily the nitrate, oxalate, and peroxide) have important uses in the defense program. These uses include tracer bullets, distress signals, and various other types of signal and warning flares used by the military services. In addition to these uses, strontium compounds are used in fireworks, railroad and highway warning fusées, welding-rod coatings and zinc refining.

Strontium minerals occur in many States, but the principal domestic deposits are in Texas, California, Arizona, and Washington. Domestic production is small and erratic. The major portion of the strontium consumption is supplied by imports from Great Britain and Mexico.

The domestic reserve of strontium minerals is large when compared to current consumption, but markets for the minerals are small, and in most areas the cost of preparing the mineral for market and transporting it to the principal consumers discourages competition with the imported material from Great Britain and Mexico. Strontium minerals are expected to continue to come from foreign sources.

Strontium minerals usually are mined by conventional open-pit methods and beneficiated by hand picking or simple gravity concentration. Strontium minerals are converted to strontium chemicals by either the soda ash or the

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[1] Work on manuscript completed October 1958.

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calcining process, the former yielding strontium carbonate and the latter strontium sulfide. Other strontium salts can be made by treating the carbonate or sulfide solutions with the acid of the desired salt.

The leading producers of strontium minerals are the United Kingdom, Mexico, and Germany. The first commercial production of strontianite was in 1840, from the deposits in Westphalia, Germany, and the English deposits came into production in 1875. Mexico did not become an active producer until 1941.

Because of the many uses for strontium compounds by the military forces in tracer bullets, signal and warning flares, and distress signals and because of the small and erratic domestic mineral production, strontium minerals are considered to be strategic and critical materials to be acquired for the national stockpile.

The strategic nature of strontium minerals and compounds requires that adequate information be available to defense planning agencies for determining stockpile objectives and defense needs during times of national emergency. This report attempts to assemble available data on this commodity.

ACKNOWLEDGMENTS

The manuscript of this report was reviewed by specialists in the Bureau of Mines, Geological Survey, other Government agencies, and industry. Their willing, constructive comments greatly increased the accuracy of this report, and the time and effort that they devoted to review are greatly appreciated.

Special acknowledgment is due E. I. duPont de Nemours & Co., Inc., and Foote Mineral Co. for their assistance in preparing this survey.

CHAPTER 1. USES, PROPERTIES, AND SUBSTITUTES

There are uses for celestite and strontianite in their mineral forms as well as uses for the numerous compounds, strontium metal (and isotopes), and various strontium alloys. By far the largest quantities of strontium are consumed as compounds, which are used primarily in pyrotechnic applications.

USES OF STRONTIUM MINERALS

MANUFACTURE OF STRONTIUM COMPOUNDS

The most important use for strontium minerals is as the basic raw material for manufacturing strontium compounds. Methods for converting the mineral to the various compounds are discussed in a subsequent section. The more important of these compounds include strontium carbonate, chloride, hydroxide, nitrate, oxalate, and peroxide. These compounds have important uses, which are discussed in some detail in the following pages.

SPECIFICATIONS

In recent years the specifications for Chemical-grade celestite have become stricter. Specifications are somewhat variable between consumers, but for conversion to strontium chemicals most users require celestite to have a minimum of 92 percent $SrSO_4$, a maximum of about 4 percent $CaSO_4$, and a maximum of about 4 percent $BaSO_4$.

The purchase specifications for celestite for the national stockpile are as follows:

P–10–R1
December 10, 1956
(Supersedes issue of
December 1, 1952)

NATIONAL STOCKPILE
PURCHASE SPECIFICATION

Celestite

1. Description

This specification covers celestite, a strontium-bearing ore, satisfactory for use in the manufacture of flares, tracers, rockets, and fusées.

2. Chemical and Physical Requirements

Each lot of celestite purchased under this specification shall conform to the following chemical and physical requirements.

a. Chemical Requirements:

	Percent by weight (dry basis)
Strontium Sulfate ($SrSO_4$)	Minimum__93.0
Calcium, as Sulfate ($CaSO_4$)	Maximum__1.5
Barium, as Sulfate ($BaSO_4$)	Maximum__2.0

b. Physical Requirements:

All celestite shall be in the form of lump or pebble ore. Not more than 2 percent by weight shall pass a U.S. Standard Sieve No. 4 (A.S.T.M. Designation E 11).

3. Packaging and Marking

a. Packaging:

All celestite shall be supplied in bulk.

b. Marking:

Each lot shall be properly identified in documents accompanying the shipment. These documents shall include the name of the product, Government contract number, country of origin, weight, chemical analysis, and name of supplier.

4. Sampling, Inspection, and Testing

Each lot of celestite shall be subject to sampling, inspection, and testing by the purchaser or his designee.

Much of the material now being imported from Mexico and England contains 94 to 96 percent $SrSO_4$, and some runs as high as 97 percent. The principal objectionable impurities are calcium, barium, and iron. Barium is objectionable because it imparts a green color to flame and therefore could not be tolerated where the compound was to be used in pyrotechnics. Calcium, though itself imparting a red color to a flame, usually occurs as calcium carbonate and consumes important quantities of acid in processing. Iron contamination is only important where the ultimate product is to be used in ceramics. Iron usually carries over to the product, unless additional chemical steps are taken to exclude it.

PROPERTIES AND USES OF STRONTIUM COMPOUNDS

The ability of strontium compounds to impart a brilliant crimson color to a flame is the basis for its primary use in pyrotechnics, flares, and fireworks. Other properties of strontium compounds and their uses are discussed later in this chapter. Table 1 gives some physical properties and uses of selected strontium compounds.

MILITARY

Most military uses for strontium, primarily pyrotechnics, utilize its property of imparting a characteristic brilliant crimson color to a flame. Apparently this use was known early in the 19th century, because several pyrotechnists' writings at that time mentioned it in their formulas. It was early mentioned as an ingredient of colored flares used by naval and military forces for illumination and tactical signaling.

Military forces today use strontium compounds in several types of pyrotechnical devices, as follows:

Tracer Ammunition.—The principal direct military uses for strontium nitrate, peroxide, oxalate, and fluoride are in tracer ammunition and flares. In World War II every fifth round from a .30 or .50 caliber machine gun had a tracer charge. These were used by marine, air, and ground forces in both day and night firing.

TABLE 1.—*Some physical properties and uses of selected strontium compounds*

Strontium compounds	Formula	Molecular weight	Specific gravity	Melting point	Other properties	Uses
Carbonate	$SrCO_3$	147. 63	3. 70	1,497° at 60 atmospheres.	Soluble in acids, slightly soluble in water.	Pyrotechnics, glass manufacture, strontium chemicals.
Chloride	$SrCl_2$	158. 54	3. 052	873° C	Soluble in water and in alcohol.	Pyrotechnics, strontium chemicals, medicine.
Hydroxide	$Sr(OH)_2$	121. 65	3. 625	375° C	Soluble in acids and in hot water; deliquescent.	Lubricants, sugar refining.
Do	$Sr(OH)_2 \cdot 8H_2O$	265. 77	1. 396	Loses water at 100° C.	Soluble in water	Do.
Iodide	SrI_2	341. 47	4. 549	402° C	Decomposes in moist air.	Medicine.
Nitrate	$Sr(NO_3)_2$	211. 65	2. 98	570° C	Soluble in water	Pyrotechnics, matches, medicine, tracer ammunition.
Oxalate	$SrC_2O_4 \cdot H_2O$	193. 65		Decomposes on heating.	do.	Pyrotechnics, tracer ammunition.
Oxide	SrO	103. 63	4. 7	2,430° C	Readily combines with water to form hydroxide.	Manufacture of strontium compounds.
Peroxide	SrO_2	119. 63	4. 56	Decomposes on heating.	Soluble in ammonium chloride sol. and in alcohol. Decomposes in hot water.	Medicine, bleaches, fireworks.
Sulfide	SrS	119. 70	3. 70	Above 2,000° C.	Soluble in water and in alcohol.	Depilatories and luminous paint.

In tracer ammunition a charge containing one or a combination of the compounds mentioned above is inserted in the base of the bullet. On firing, this charge is ignited and burns brilliantly during flight. This permits the gunner to judge the accuracy of his aim. Figure 1 illustrates the effect of burning tracer bullets.

Military Flares.—The military use of strontium (nitrate and carbonate), second in importance, is in flares and signal devices. These flares are used for varied tactical and distress or rescue signaling and for illumination. They are made in various sizes, shapes, and types and usually consist of red flares and some ejecting or propelling device. (See fig. 2.) A strontium flare used by military aviators will float on water and thus expose the movements of enemy naval units. The army provides a special mechanism to be attached to a rifle for firing flares, and there is also a type of flare that can be released from a submerged submarine. Strontium nitrate comprises about 40 percent of the formulation by weight. The total composition weight for any one item varies from one-half ounce to 16 ounces. Strontium nitrate for this purpose is covered by Specification JAN–A–177. Ordnance Pamphlets 1511 and 1177 describe pyrotechnic devices that use strontium in flare compositions. They are classified confidential. Copies are available from the Ordnance Publications Distribution Center, Navy Yard, Washington 25, D.C., to those having appropriate security clearance credentials. Lithium nitrate has been considered and tested as a substitute for strontium nitrate in flare compositions but price, hygroscopicity, and color rule it out.

Marine Distress Signals.—Marine distress-signal equipment consists of handheld flares, parachute flares, a pistol for firing them into the air, and rockets for use on ships. Some of the

(Courtesy, Public Information Division, Office Chief of Information and Education, Department of Army.)

FIGURE 1.—Tracer bullets and other pyrotechnics light the night, during a fire power demonstration.

larger distress rockets can be fired several hundred feet into the air, and some release showers of "stars." Similar red flares can be dropped, parachuted, shot from aircraft or released by submarines. A typical handheld distress signal is illustrated in figure 3.

Rules and regulations necessary to carry out the provisions of the law affecting the merchant marine (Title 52 of the Revised Statutes of the United States (secs. 4399–4500)) and to implement various international conventions for safety of life at sea and other treaties are published and administered by the United States Coast Guard (*43*).[4] These rules and regulations require that lifeboats for all passenger vessels navigating the ocean or coast shall be equipped with 12 approved hand red flare distress signals in a watertight container, and 12 approved parachute red flares with an approved means of projecting them, or 12 handheld rocket-propelled parachute red flares, all in a portable watertight container. Vessels in coastwise service must carry 12 flares for each five lifeboats.

Lifeboats on passenger vessels in service on the Great Lakes must carry 12 red hand flares or 6 hand flares and 12 parachute flares or 6 hand flares and an approved flashlight.

Lifeboats on vessels in service on other lakes, bays, sounds, or rivers are not required to carry flares.

All passenger vessels in ocean and coastwise service must carry in the pilothouse or on the navigator's bridge 12 handheld rocket-propelled parachute red flare distress signals.

All lifeboats on tankships operating on ocean or coastwise routes must be equipped with 12 handheld red flares and 12 parachute red flares. Such vessels also must carry, in the pilothouse or on the navigator's bridge, 12 approved handheld red flares, and vessels of 500 gross tons and over must carry 12 handheld rocket-propelled parachute red flares.

The regulations for cargo and miscellaneous vessels are similar. Specifications for handheld red flare distress signals, handheld rocket-propelled parachute red flares, pistol-projected

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[4] Italicized numbers in parentheses refer to items in the bibliography at the end of this report. Page references refer to pages in the items and not in this report.

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parachute red flares, hand combination flares, and smoke distress signals are available from the United States Coast Guard, Washington, D.C.

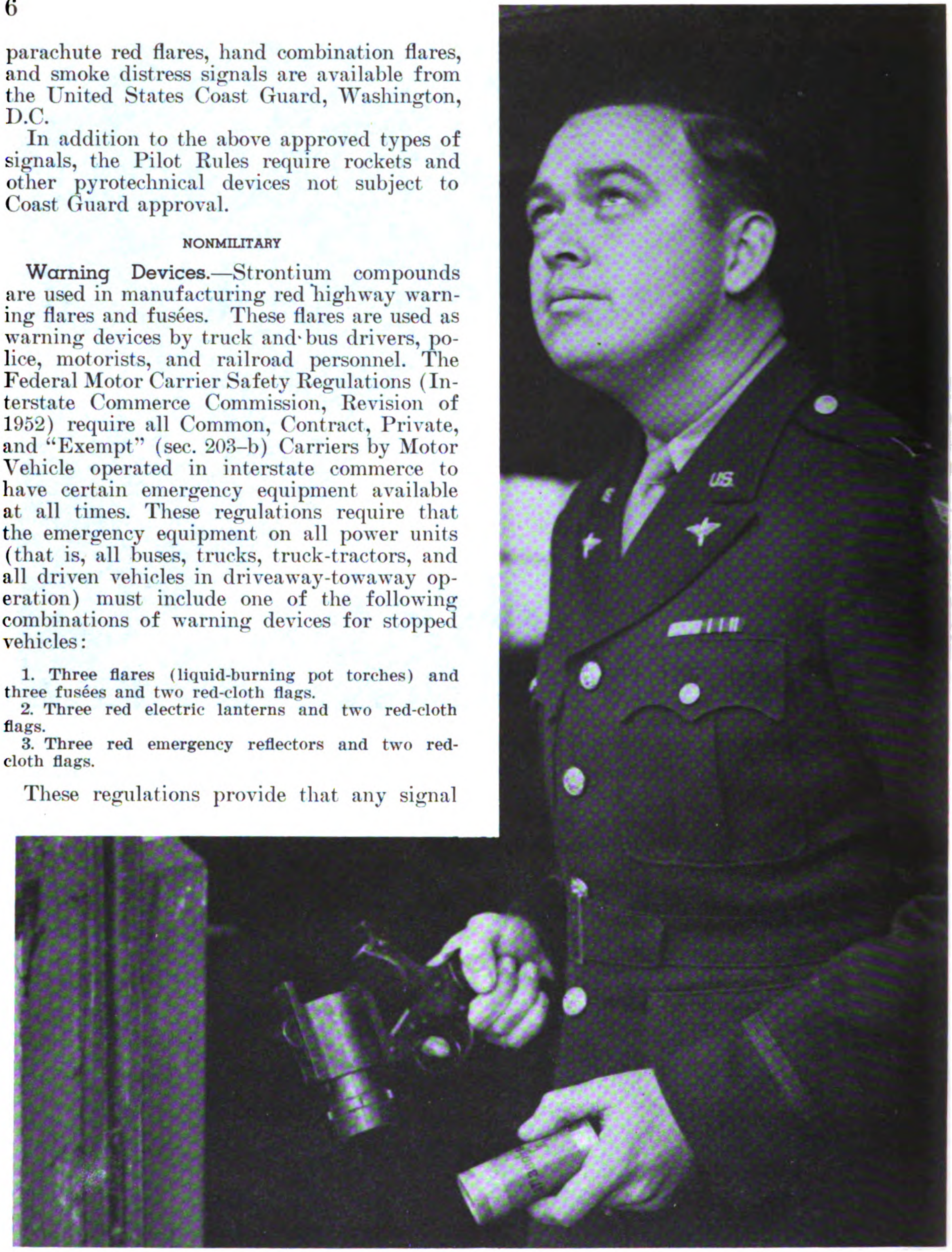
In addition to the above approved types of signals, the Pilot Rules require rockets and other pyrotechnical devices not subject to Coast Guard approval.

NONMILITARY

Warning Devices.—Strontium compounds are used in manufacturing red highway warning flares and fusées. These flares are used as warning devices by truck and bus drivers, police, motorists, and railroad personnel. The Federal Motor Carrier Safety Regulations (Interstate Commerce Commission, Revision of 1952) require all Common, Contract, Private, and "Exempt" (sec. 203–b) Carriers by Motor Vehicle operated in interstate commerce to have certain emergency equipment available at all times. These regulations require that the emergency equipment on all power units (that is, all buses, trucks, truck-tractors, and all driven vehicles in driveaway-towaway operation) must include one of the following combinations of warning devices for stopped vehicles:

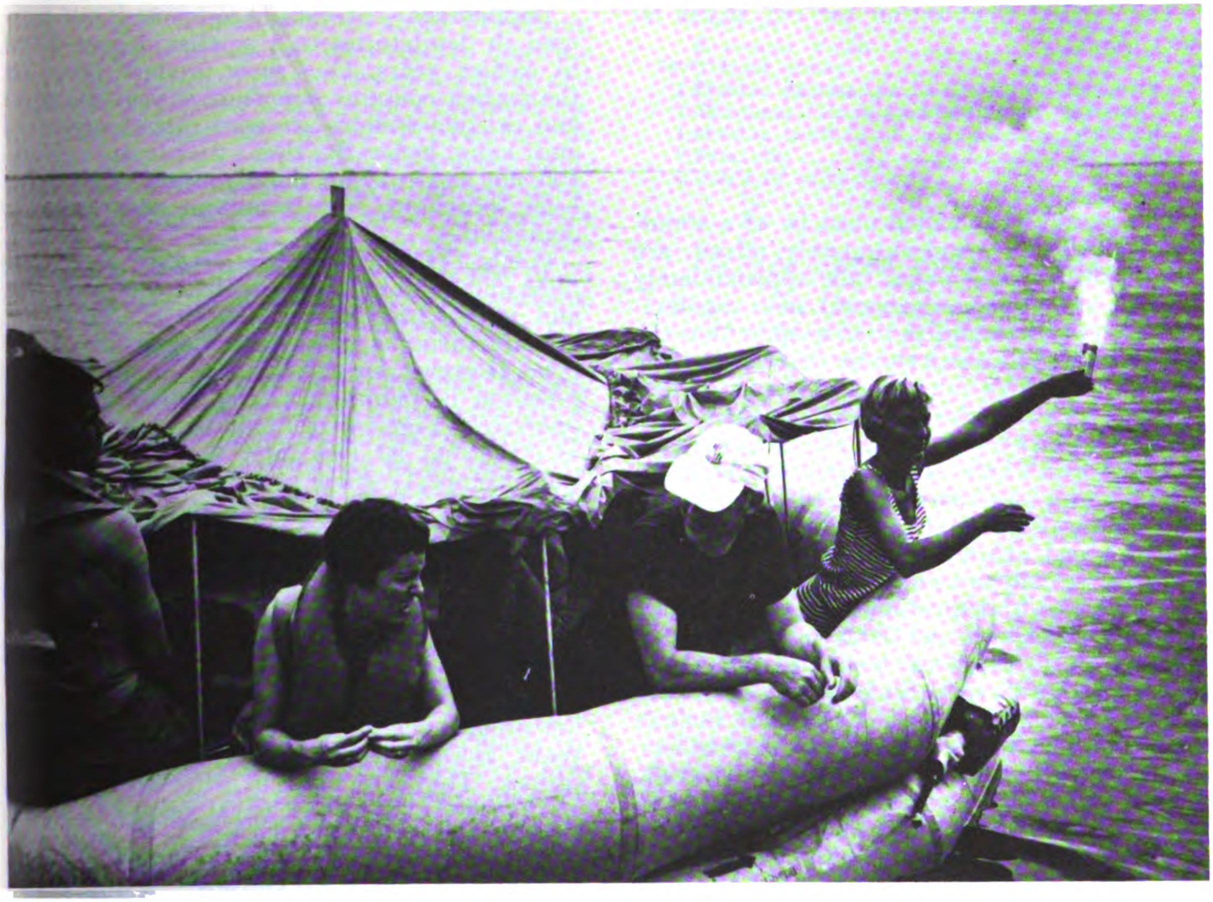
1. Three flares (liquid-burning pot torches) and three fusées and two red-cloth flags.
2. Three red electric lanterns and two red-cloth flags.
3. Three red emergency reflectors and two red-cloth flags.

These regulations provide that any signal



(Courtesy of Air Force, Department of Defense.)

FIGURE 2.—Air Force Captain, in World War II, holding a Very pistol and flare cartridge ready to signal aircraft. Strontium compounds are used in this type of flare.



(Courtesy, U.S. Coast Guard).

Figure 3.—Strontium compounds are used in marine distress signals such as the one held by an airline stewardess during a practice ditching.

produced by a flame shall not be carried on motor vehicles used in transporting explosives, flammable liquids, or flammable compressed gases in cargo tanks or in any motor vehicle using flammable compressed gases as a motor fuel. In such instances, three electric lanterns or three red emergency reflectors shall be carried.

It is required that fusées used as protective devices shall comply with the specifications of the Bureau of Explosives, 30 Vesey St., New York 7, N.Y., dated December 15, 1944, and be so marked.

All States have laws or regulations regarding the use of emergency protective devices within the States. Most of these laws are patterned on the Federal Motor Carrier Safety Regulations. Nearly two-thirds of the States require that fusées be carried on certain types of vehicles.

In addition, most automobile and trucking associations recommend that emergency protective devices, including either fusées or flares, be carried in certain types of vehicles. These regulations, laws, and recommendations usually provide that, when a vehicle is disabled, stopped, or parked on the traveled portion of a highway or the shoulder of a highway, a lighted fusée shall be placed immediately on the traveled portion of the highway at the traffic side of the vehicle. The courts have ruled companies or individual drivers liable when such precautions have not been taken.

Although no Federal regulations specifically require it, railroads for many years, as a safety practice, have used red flares and fusées for emergency signaling. All railroad companies require that a considerable number of 5-minute and/or 10-minute fusées be carried at all times on each operating passenger and freight train. When a train is slowing or stopping, the flagman is required to place these fusées in such a way that trains following will be warned.

The typical composition for red fusées is: (*20*)

	Percent
Strontium nitrate	71.1
Potassium perchlorate	13.1
Sulfur	11.1
Sawdust	4.2
Charcoal	.5

The components, which must be of a standard fineness, dry, and intimately mixed, are inserted in a strong paper tube approximately 7 inches in length and about 1 inch in diameter. The tube usually has a spike on the bottom that permits it to be driven into the ground.

Fireworks.—The familiar and impressive red color of many types of fireworks and pyrotechnical exhibitions is produced by the addition of strontium compounds, such as the nitrate and carbonate. Fireworks displays and pyrotechnical exhibitions have been used for centuries to add splendor and spirit to such celebrations as inaugurations, national holidays (such as Independence Day in the United States), fairs, religious festivals, and many other types of events. Such pyrotechnics are of numerous and diverse types and include colored lights, torches, flares, lances, rockets, Roman candles, stars, gerbs, fountains, wheels, saxons, pinwheels, comets, sparklers, and fire sticks. Fireworks displays have a religious significance to some people; for example, in some religious events they are used to drive away evil.

Zinc Refining.—In preparing high-purity electrolytic zinc, strontium carbonate is used to remove lead from the cathode zinc. Under license from American Smelting and Refining Co. (U.S. Patent 2,539,681) $SrCO_3$ is added to the feed solution at the rate of 5½ to 6½ pounds per ton of zinc. Strontium carbonate is said to be effective only when the lead content is higher than 20 grams per ton of zinc.

Welding-Rod Coating.—The welding industry uses small quantities of Technical-grade strontium carbonate as a coating on special alloy-type welding rods to stabilize the arc. This use is limited to about 5,000 to 10,000 pounds annually.

For some years fluorspar has been the principal flux used in coating stainless steel welding rods; however, the fluorine fumes given off during welding are a potential hazard to the welder. Tests have been made using strontium carbonate as a flux, and the results reported indicate that, while the strontium carbonate slag had all the advantages of fluorspar, it had none of its possible harmful affects on the health of the welder.

Depilatories.—Strontium compounds are now used in depilatories to a smaller degree than in earlier years. One such product now on the market contains strontium sulfide. Barium and calcium sulfides are used interchangeably and more generally than strontium sulfide. Barium and calcium thioglyconates also have been substituted for strontium chemicals in depilatories.

Paints.—Ground celestite has been used as a filler and brightening agent in colored paints, and it has been used in place of barite in manufacturing a product analogous to lithopone. However, strontium's most important application in paints is as the sulfide in phosphorescent pigment in luminescent paints and as strontium 90 (see later section on strontium isotopes), which acts as the "exciter" in luminescent pigments where the glow source or "phosphor" is usually a metallic sulfide, such as zinc and/or cadmium sulfide that is activated by a trace or a very small percentage of a metal such as silver.

Strontium sulfide luminescent paints have been used since the early 1930's; the strontium 90 used in excited pigments is a product of the atomic energy program of the last few years. Both products have important applications. They are used in after-dark guides and markers, such as on naval vessels to mark walking areas, to identify life rafts and ammunition boxes, or to indicate bulkhead doors and escape hatches of aircraft. Nonmilitary uses include billboards, advertising signs, dials and instrument panels, artwork and interior decorating, street numbers, painting as an aid to lighting, draperies and curtains, costumes, and phototemplet reproductions.

A newly developed use for strontium compounds in paints is addition of the chromate to aluminum paints to prevent package corrosion.

Greases.—Strontium soap greases have been made commercially by one producer in California, who uses the strontium hydrate $Sr(OH)_2 \cdot 8H_2O$(*33*). They have been prepared from a wide variety of soap stocks, such as tallow, lard, sperm, and peanut oil. The fatty acids have included such materials as tallow fatty acids (oleic, stearic, myristic, and ricinoleic) and acids from oxidized wax. Some desirable properties of strontium greases include their reversibility over wide temperature limits; resistance to emulsifying and disintegrating effects of water; some resistance to the leaching action of such light hydrocarbons as gasoline; resistance to oxidation upon exposure to elevated temperatures; and relatively superior rust protection without rust inhibitors. The strontium soap content of these greases has ranged from about 20 to about 30 percent. This type of grease has been used to lubricate bearings in the drying ovens in a rubber and tire plant; tapered bearings on a conveyor operating at about 350° to 400° F.; bearings on motor generators for running fluorescent lighting on a railway train; general-purpose lubricant in a food-processing plant; kiln bearings; and aircraft bearings. It is also used on glass joints on large distillation units because of its resistance to water condensate, hydrocarbons, and heat and on papermaking machines employed in making cellophane.

Ceramics.—A great deal of research has been done on strontium minerals and compounds in various types of ceramics. Strontium carbonate is now employed extensively as an ingredient in certain ceramics, such as low-temperature pottery and dinnerware glazes, high china and electrical porcelain glazes, other glazes and frits, china bodies, enamel, and glasses.

The following advantages over other basic oxides used in glazes have been claimed for strontia (*36*): It lessens pinholing and blistering; increases firing range and improves firing control by a gain in complexity of composition; lowers acid solubility, particularly in lead-containing glazes; increases fluidity; promotes interface reactions; improves glaze fit and scratch resistance when replacing calcium and barium or both; and aids in developing low-temperature vitreous glazes and leadless glazes.

Lead compounds could be substituted for strontium carbonate in many of its ceramic applications. However, there may be some toxicity dangers in using lead; being nontoxic, strontia is less hazardous. Other oxides, such as zinc, magnesium, barium, and calcium, have been used in various ceramic bodies and glazes, therefore are substitutes of varying relative efficacy, depending on the application.

Dielectrics.—Strontium titanates, usually mixed with barium or other titanates, are components of various ceramic dielectric materials for use in electrical condensers. Such bodies are readily producible by mass production methods; are relatively small; have capacitance that remains constant or have predetermined variance; and provide simple and rugged construction.

Transparent colorless crystals of strontium titanate are produced commercially. The physical properties of these crystals show that they may have optical uses and if properly cut and polished may be used as gem stones (*49*).

Some physical properties of strontium titanate crystals:

Formula	$SrTiO_3$
Molecular weight	183.53
Crystal system	cubic
Specific gravity	5.124
Hardness (Mohs scale)	6 to 6.5
Melting point	2080° C.
Fracture	conchoidal
Index of refraction:	
N_c	2.380
N_d	2.409
N_f	2.488
Dielectric constant (100 kc)	310

Sugar.—In Germany sugar-beet molasses is treated with strontium hydroxide (the Scheibler process) to recover the sugar. In this process an excess of strontium hydroxide is added to a solution of the molasses at a temperature exceeding 100° C., and the mixture is agitated to precipitate strontium disucarate. The precipitate is filtered and washed with a boiling solution of strontium hydroxide and then dissolved in a cold solution of the hydroxide. After several days carbon dioxide is passed through the solution to precipitate the strontium as carbonate. This is reconverted to the hydroxide by calcining and dissolving in water. The sugar solution is crystallized to produce a pure sugar.

The methods used for recovering beet sugar from molasses in the United States are the lime or Steffen process and the barium process. Although the economics of the operation, the difficulty of recovering the strontium, and the lack of purity of the product have been mentioned as reasons for not using the strontium process, it is not clear why it is not used, in view of the many advantages claimed for it.

The Scheibler process is still used by most of the refineries in East Germany. However, in West Germany it was superseded before World War II by the BARSI process, involving use of barium silicate, for which more economical operation and purer product are claimed.

OTHER USES OF STRONTIUM MINERALS

In addition to being the basic raw materials for manufacturing strontium compounds, celestite and strontianite also have other uses in the mineral form. The major use for the minerals is as the raw material for manufacturing chemical compounds.

DRILLING MUDS

Celestite has been used as a component of well-drilling muds, principally to add weight. For this purpose it was ground to pass 95 percent through a 325-mesh screen. Theoretically celestite has a specific gravity of 3.95. Actually the material used for well drilling was a rather impure product running approximately 85 percent strontium sulfate and had a specific gravity of about 3.69. It was used in considerable quantities from the late 1930's until about 1943, when the patent on the use of barite in drilling muds expired and with it the exigible royalty of $17 per ton that had permitted celestite to compete with it. Because of its less suitable properties, celestite in this use could be called only a substitute. After 1943 its use in drilling mud dwindled rapidly, as barite with specific gravity of 4.5 (commercially about 4.25) could be purchased at about the same price. The difference in specific gravity permits preparation of a mud weighing about 20 pounds per gallon, using barite, and only about 14 pounds per gallon, using celestite.

RUBBER FILLER

Ground celestite has been tested as a filler in vulcanized rubber. Compared with ground barite and precipitated barium sulfate, the ground celestite was the least detrimental to natural aging (*7*). Studies have shown that the mechanical properties of vulcanizates containing equal volumes of barite and celestite were similar, except that, at high concentrations, celestite gave lower permanent sets (*27*).

There is evidence that ground celestite is a satisfactory substitute for barite in various types of rubber products. It also has been used occasionally as a filler in paints, phonograph records, sealing waxes, and sealing compounds for storage batteries.

CAUSTIC SODA

High-purity caustic soda, often called rayon grade, is required in producing viscose rayon and cellophane. Impurities cause various deleterious effects, such as poor color, abnormal chemical processing, and inferior end products.

Much of the impurity in commercial caustic soda solutions produced by electrochemical methods occurs as a ferrate ($FeSO_4$) with possibly some ferrite (FeO_3) and perferrite (Fe_2O_4) ions. Removal of these impurities by finely ground strontium minerals is due to adsorption of the ions on the mineral particles, which in turn settle from the solution. At 30° C. celestite is a better adsorbent than strontianite. Increase in temperature increases the amount of impurity removed by a given quantity of strontium mineral. At higher temperatures strontianite approaches celestite in ability to remove iron impurities.

Calcium and barium sulfates and carbonates do not exhibit as good adsorptive properties as those of strontium for higher valence iron ions from caustic solution (*17*).

In papermaking, caustic soda is used for bleaching and pH control. Commercial pulp bleaching begins with treatment by chlorine gas. The chlorine is then extracted with a dilute caustic soda solution. Iron and manganese sometimes present in the caustic soda may impose serious difficulties. They act as oxidation catalysts and produce a pulp of lower brightness or whiteness and cause excessive reversion (the phenomenon of the pulp losing whiteness a relatively short time after manufacture). Celestite and strontianite, alone or combined, are useful agents to lower the iron or manganese content of the caustic soda used.

STEEL

Several German, English, and American steel producers have used strontianite to aid in desulfurizing the best grades of open-hearth steel. Strontianite acts as a flux, producing a fluid and strongly basic slag. Fluorspar has somewhat the same effect on slag, but attacks furnace linings and is less effective in removing sulfur. Strontium oxide, being basic, is more efficacious in removing both sulfur and phosphorus.

Strontianite has been used on a semicommercial scale in Europe for desulfurizing and dephosphorizing steel. Although a few tons of strontianite has been shipped to domestic manufacturers of ferrous alloys, the use of strontium in steelmaking is less promising in the United States than in Europe because of the high quality of domestic iron ores (*10*).

STRONTIUM METAL AND ALLOYS

Strontium is a divalent element in the second group of the periodic system. It is one of the alkaline-earth metals (a group that also includes calcium, barium, radium; and some include beryllium and magnesium), so called because their properties are intermediate between the true alkali and the real earths. The pure metal is silvery white, with a specific gravity of 2.5 or 2.6, a melting point of 800° C., and a boiling point of 1,115° C., and is slightly alkaline. It does not occur uncombined in nature. Strontium metal (like calcium and barium) decomposes water (though rather slowly at ordinary temperatures) with evolution of hydrogen and formation of strongly alkaline hydroxides, which are only slightly soluble. Strontium is a relatively poor conductor of electricity.

PROPERTIES

Chemical symbol	Sr.
Atomic weight	87.63
Atomic number	38
Specific gravity	2.5–2.6
Melting point	800° C.
Boiling point	1,115° C.
Crystal structure	Cubic
Hardness	1.8

USES

Because of its inherent instability, strontium metal has little use. At present it is used in getter alloys to remove traces of gas from vacuum tubes and as a scavenger in metallurgy. Little is known of its alloying properties. Addition of small percentages of strontium to lead increases its hardness and durability for use in storage batteries. Strontium-tin, strontium-lead, strontium-aluminum, and other alloys have been used in small quantities for purifying alloys and metals.

Strontium in copper castings increases hardness and lessens blowholes.

SUBSTITUTES

There are no satisfactory substitutes for strontium compounds in most of their pyrotechnic, ammunition, and chemical uses.

Many materials impart red color to flame, but no substitute has been found with the brilliance and visibility range of strontium compounds. Calcium and lithium impart red color to flame, but properties such as deliquescence, reactivity, burning characteristics, and others make compounds of these elements unsuitable substitutes for strontium compounds in ammunition and in certain other pyrotechnical applications.

Although strontium metal and alloys have been used as getters in extracting traces of gases from electronic tubes, barium is interchangeable with strontium for this purpose.

In purification of caustic soda, it has been recently reported that a magnesia limestone process and an ammonia process have been devised as substitutes for strontium minerals in this purification process.

CHAPTER 2. RESOURCES

Occurrences of celestite minerals are widespread throughout the world, although only in a few deposits is the ore of such a grade and nature that a commercial product can be recovered. In the United States the deposits that have attracted the most attention as potential sources of strontium minerals are in southern California, Arizona, the western part of Washington, and central Texas. Occurrences of strontium minerals have been reported in Arkansas, Utah, Ohio, Michigan, Missouri, New York, Pennsylvania, Tennessee, and West Virginia. Figure 4 shows the location of strontium mineral deposits in the United States.

Deposits or occurrences of strontium minerals are also found in the United Kingdom, Mexico, Newfoundland, Australia, Germany, Tunisia, Spain, U.S.S.R., France, India, Pakistan, Argentina, and Sicily.

MINERALOGY AND GEOLOGY

MINERALOGY

The important strontium minerals are celestite ($SrSO_4$) and strontianite ($SrCO_3$).

Celestite, sometimes called celestine, crystallizes in the dipyramidal class of the orthorhombic system. Its crystals are commonly tabular and closely resemble those of barite. The mineral also occasionally occurs in radiating fibrous and granular form.

Celestite has perfect basal (001) and prismatic (110) cleavage, with angles of about 104° and 76°. It has a hardness of 3–3½ and a specific gravity of 3.95–3.97. Its luster is vitreous to pearly; it usually is colorless or white, with a faint blue or red tinge, and is transparent to translucent. The mineral fuses at 3½–4 on the scale of fusibility and colors a flame crimson (strontium). The flame color is a distinguishing feature and can be used to differentiate between celestite and barite, as the latter gives a green flame.

The theoretical composition of celestite is SrO–56.4 percent, SO_3–43.6 percent (*21*). Barite and celestite occur in a solid-solution series (baritocelestite or celestobarite) in about the ratio Ba : Sr = 1 : 1, but most material is near one end or the other of the series. Calcium replaces strontium in celestite (calciocelestite or celestocalcite) to a limited extent, about the ratio Ca : Sr = 1 : 11.

Strontianite crystallizes in the orthorhombic system, dipyramidal class. Crystals are radiating, columnar, fibrous, or granular. It has good prismatic (110) cleavage, a hardness of 3½–4, and a specific gravity of 3.7. Its luster is vitreous; it is white, gray, yellow, or green, and is transparent to translucent. The theoretical chemical composition is SrO–70.1 percent, CO_2–29.9 percent. Calcium is almost always present, replacing strontium up to the ratio of Ca : Sr = 1 : 4.5.

Strontianite is nearly infusible but on intense ignition swells, forms fine branches, and produces a crimson flame. It effervesces in hydrochloric acid, and the medium dilute solution will give a precipitate of strontium sulfate on addition of a few drops of sulfuric acid; no precipitate will form in the very dilute solution. The mineral is characterized by its effervescence in hydrochloric acid and its high specific gravity and can be distinguished from witherite and aragonite by flame test and from celestite by poorer cleavage and effervescence in acid (*21*).

GEOLOGY

Strontium in small quantities or traces is common in igneous rocks; according to Clarke (*3*), the content averages about 0.034 percent. It is more abundant than copper, lead, zinc, fluorine, nickel, and lithium but less abundant than vanadium, carbon, zirconium, chromium, sulfur, or barium. Strontium is less abundant in sedimentary rocks than in igneous rocks. However, most commercial or potentially commercial deposits of strontium minerals occur in or near sediments or sedimentary rocks.

According to Rankama and Sahama (*38*), no strontium mineral is known that is formed during the main stage of crystallization of igneous rock; notwithstanding its relatively high abundance, strontium only occasionally forms independent minerals in igneous rocks. The strontium minerals belong to the pegmatitic-pneumatolytic and hydrothermal stages of crystallization, and even in rocks formed during these stages they are rare. The bulk of strontium is concealed in the principal minerals of igneous rocks, basic igneous rocks being the poorest in strontium and acidic rocks the highest.

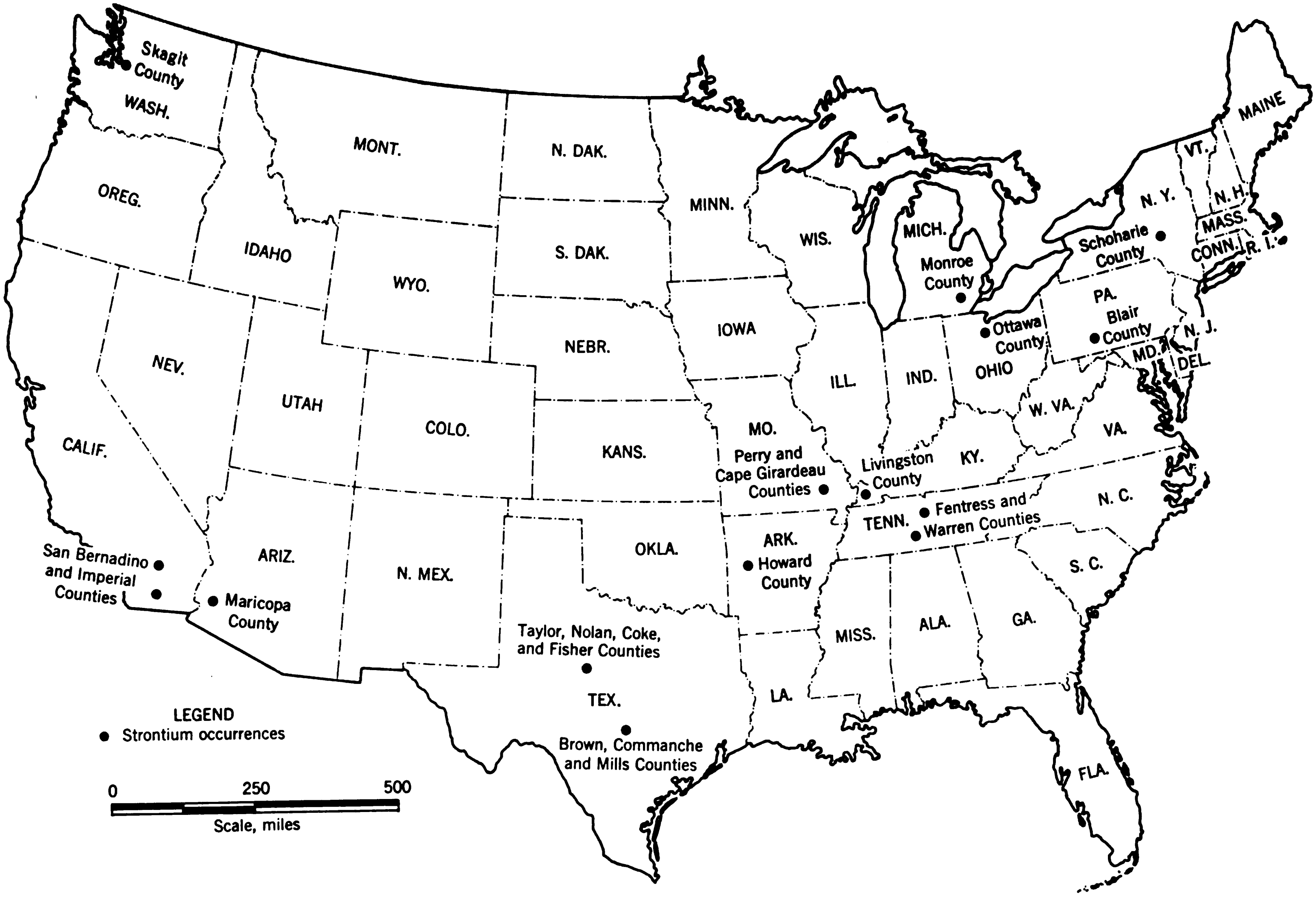


FIGURE 4.—Strontium mineral occurrences in the United States.

In thermal waters strontium is enriched in relation to calcium, and its content is higher than that of barium because barium sulfate is less soluble than strontium sulfate. Most commercial deposits or potentially commercial deposits of strontium minerals occur in or near sedimentary rocks, chiefly as beds or lenses associated with gypsum, anhydrite, or rock salt; in cavities or veins and disseminated in limestone and dolomite; or disseminated in shales, marls, and sandstones. It may also be found associated with metalliferous ores, such as galena and sphalerite.

When certain conditions prevail, masses of celestite may be deposited from sea water along with anhydrite. Since considerable celestite is present in some saline deposits and none in others, it is believed that its deposition may depend upon the sulfate and chloride ions in the sea water reaching a certain, but up to the present time, unknown concentration. Examples of large sedimentary celestite deposits are those in the Keuper formation (Triassic) of England, the Zechstein (Permian) of Germany, and some of the Cretaceous deposits in Texas and Arkansas (*35*).

The celestite deposits of Sicily and some of the deposits in southeastern California and western Arizona are believed to be derived from solfataras.

Strontianite is usually regarded as a secondary mineral resulting from the weathering of celestite.

WORLD RESERVES

DOMESTIC

Although exploration of domestic deposits has consisted largely of simple observation and evaluation and on the whole has been cursory, it is apparent that the aggregate tonnages in these deposits greatly exceeds anticipated requirements for many years. The Federal Geological Survey has estimated the domestic resources at 3.5 million tons of material containing at least 85 percent $SrSO_4$. However, when considering resources it is essential to know whether the material can be beneficiated to meet the current rigid specifications of most processors. For instance, some celestites and strontianites have calcium and/or barium locked so intimately in the crystal that these elements cannot be removed except by chemical processes.

A vast untapped resource of strontium lies in the earth's hydrosphere. This element is one of the more abundant in sea water, having a concentration of about 13 grams per ton (*38, p. 290*). Only eight other elements (Cl, Na, Mg, S, Ca, K. Br, and inorganic C) are present in higher concentrations. Some of these are at present recovered from this source; and, if demand warranted, strontium could probably be recovered.

FOREIGN

Little is known of reserves in foreign countries. However, there are indications that overall resources are large and that reserves of several individual deposits are substantial in terms of current and anticipated requirements.

UNITED STATES DEPOSITS

ARIZONA

MARICOPA COUNTY

Aguila.—A celestite deposit about 15 miles southeast of Aguila is on a spur in a valley at the northeast end of the Vulture Mountains, a low range composed of volcanic flows, and tuffs several thousand feet thick. The beds are extensively faulted and tilted into intricate structural patterns, and layers of celestite of varying thickness alternate with the shaly tuffs. A fanglomerate of granitic and volcanic debris surrounds the base of the spur. Overlying the fanglomerate is a shaly tuff that extends upward about 100 feet to a narrow bench composed of beds of celestite-bearing rock that weather as a cliff. The ground above this bench rises steeply to an old terrace level, from which material has washed down over most of the slopes. Other celestite rock is found in the area but is mostly hidden by wash. Beds of celestite occur in the shaly tuff member at several horizons, and the area has been highly silicified.

This district has not been well explored, but outcroppings and pits indicate that celestite underlies an area of at least 18,000 square yards, and at least 180,000 short tons of celestite-bearing rock probably can be found in the area (*8, p. 11*). The beds of celestite outcrop prominently and could be mined by open-pit methods. There has been a road to the deposit and the Atchison, Topeka & Santa Fe Railway runs through Aguila.

Gila Bend.—Celestite occurs about 15 miles south of Gila Bend and about 3 miles east of Black Rock siding of the Tucson, Cornelia & Gila Bend Railroad. The deposits, which are covered by a thin layer of gravel, are on the northwest side of a low group of hills in a series of tuffs underlying the basaltic lavas that form the mountains. The celestite zone, with associated gypsum, sandstone, and conglomerate, strikes northerly, with steep dips to the east. In the southern part of the zone the celestite beds outcrop at several places over a

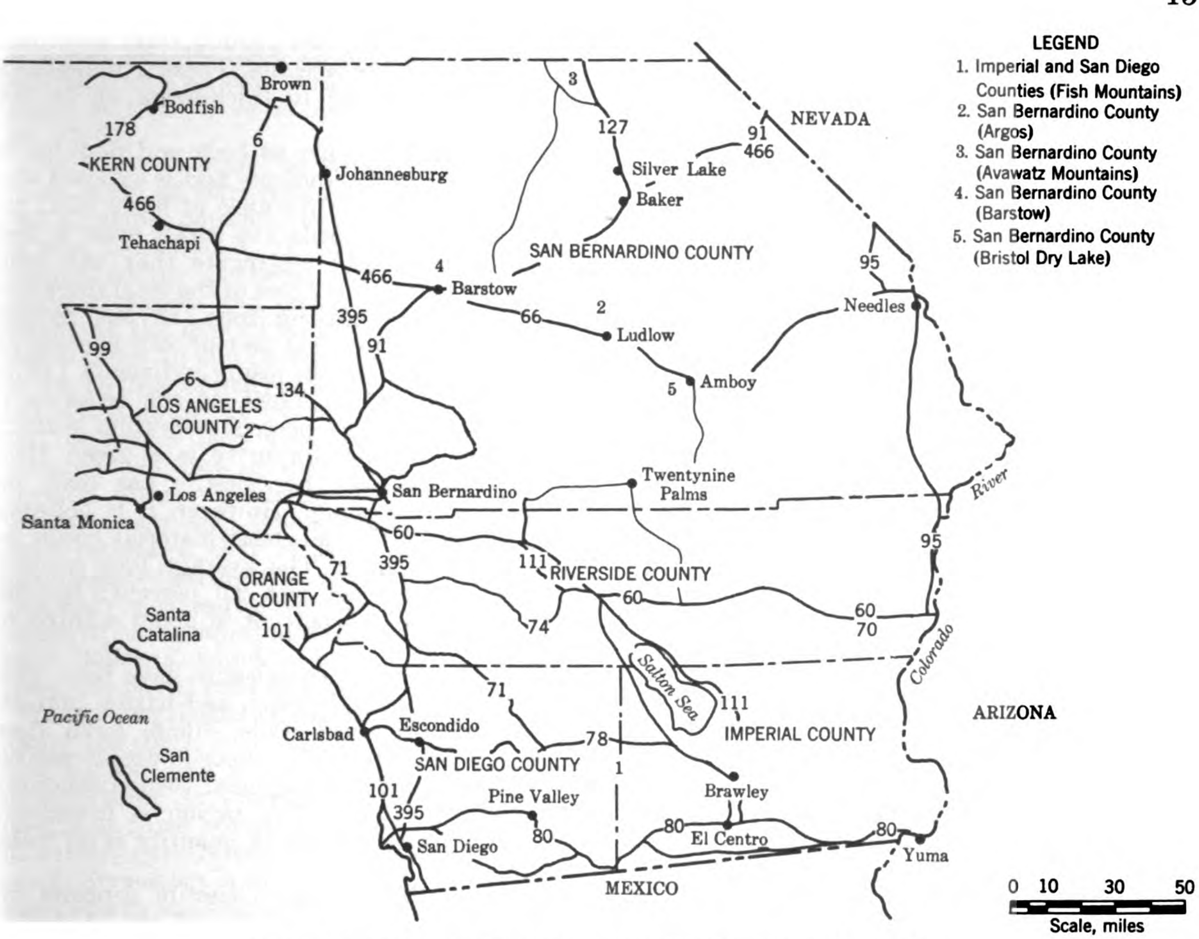


FIGURE 5.—Strontium mineral occurrences in Southern California.

distance of 750 feet, strike N. 65° E., and dip 28° SE. The most important bed ranges from 2 to 3 feet in thickness and can be traced for the entire distance, but at other places there are less continuous beds interbedded with tuffs, which increase the thickness of the zone to a maximum of 6 feet. Some of the best celestite in the area averages approximately 87 percent $SrSO_4$; however, some of the rock may be too high in barium and calcium to have commercial value. There is 9,000 short tons of celestite rock. Although it has not been completely examined, the celestite zone is believed to extend northward along the strike, and if this assumption is true the quantity of celestite rock may be larger.

ARKANSAS

HOWARD COUNTY

Dierks.—A deposit of celestite near Dierks has been investigated by the Hardy Mining Co., Little Rock, and by Baroid Division of National Lead Co. The celestite occurs as lenses and nodules of sedimentary origin in the De Queen limestone member of the lower Cretaceous Trinity Formation.

CALIFORNIA

Several deposits of celestite and/or strontianite are known in southern California. Small quantities of ore have been mined, and some deposits are large and high grade enough to have commercial interest. The more important of these deposits are in San Bernardino, Imperial, and San Diego Counties. The deposits are scattered, but all are associated with an extensive series of Tertiary sediments, mostly limestone, gypsum, dolomite, magnesite, salt, and volcanic ash. The strontium minerals occur in the soluble derivatives of weathering of these materials. Figure 5 shows the locations of the California strontium mineral deposits.

IMPERIAL AND SAN DIEGO COUNTIES

Fish Mountains.—A deposit of celestite associated with gypsum in the Fish Mountains was described by Moore (*8, pp. 15–16; 11*). The occurrence in Imperial County is in the Salton

Sink about 26 miles north of Plaster City in sec. 18, T. 13S., R. 9E., and about 1 mile east of the gypsum quarries of the Pacific Portland Cement Co. The deposit is just east of the San Diego County line. In this area a thick gypsum bed rests on weathered granitic rocks, and the celestite rock forms a dissected cap of nearly flat beds on an isolated hill of the gypsum. A section through this hill is as follows:

Summit	*Feet*
Celestite rock, massive, white	10
Interbedded gypsum and celestite	3
Gypsum; a few nodules of celestite near top	100
Deeply weathered granite.	
	113

The celestite rock is uniformly pure and free from silicified material, and the hill reportedly contains more than 10,000 tons of celestite rock. Similar outcrops in San Diego County west and northwest of the Pacific Portland gypsum quarry have also been described (*46 pp. 5–7*). Here celestite forms a cap on several small hills west of the road from Ocotillo to the quarry and north of Fish Creek Wash, in San Diego County. The oldest exposed rock is a thick breccia, composed mainly of granitic fragments overlain by gypsum. Celestite caps the highest points in the area, and apparently formerly occurred as lenses in the gypsum; it now is present as erosion remnants. The celestite beds range from 2 to 8 feet in thickness, but the interval between the base of the gypsum and the base of the celestite varies from about 90 to 150 feet, indicating that all the celestite is not at the same stratigraphic horizon. Pan Chemical Co., Claremont, Calif., has mined small tonnages of celestite from time to time.

The celestite of this area reportedly has a low calcium and barium content and a $SrSO_4$ content averaging 94 to 97 percent (*40*).

SAN BERNARDINO COUNTY

Argos.—Several celestite-bearing beds outcrop in the dissected fan heads at the base of the southern slope of the Cady Mountains. This area, about 3 miles northwest of Argos Station (about 8 miles northwest of Ludlow) on the Atcheson, Topeka & Santa Fe Railroad, comprises secs. 19, 20, 29, and 30 of T. 8 N., R. 7 E. The deposits in this area are inferred to contain more than 2 million tons of celestite, with the possibility of several times that tonnage.

The Cady Mountains consist of a succession of intensively folded and faulted, brightly colored lavas, tuffs, and lacustrine deposits. Along the southern base of the mountains a coarse tuff, part of the volcanic series, is exposed. This is overlain by lacustrine sediments composed of fine, thin-bedded clays and tuffs which contain the celestite. These sediments, in places, are exposed in thicknesses up to 700 feet.

The celestite occurs as beds and nodules in the clay and tuff sediments and is exposed discontinuously over a distance of 6,300 feet. Individual celestite beds are rarely over 2 feet thick; however, in aggregate they can constitute as much as 112 feet of the total thickness of the celestite-bearing zone. In one section celestite constitutes 111 feet or 29.8 percent of the 372 feet of the enclosing sediments (*46 p. 42*). The average content of the celestite is reportedly about 81 percent strontium sulfate. The most common impurity is a green clay, and in some beds the celestite has been replaced by chalcedony. However, it is believed that much of this siliceous material could be avoided in mining. The average lime content of samples assayed was 2.0 percent; barium oxide exceeded 1.0 percent in about a third of the samples.

Small quantities of celestite have been produced from these deposits, and barite, manganese, and Chemical-grade calcite have been mined in the area. The deposits are accessible by about 3 miles of ungraded roads branching from Highway 66. The region is extremely arid; the nearest water in quantity is 30 miles west.

Avawatz Mountains.—Celestite deposits occur on the northeast slope of the Avawatz Mountains near the southern end of Death Valley. The area is accessible by about 14 miles of poor roads from the paved highway at Salt Springs. The nearest railroad loading point is 60 miles from Salt Springs at Dunn Station. The deposits are in a series of Tertiary lake sediments that contain extensive beds of gypsum and salt complexly faulted, crushed, and folded between igneous rocks. Celesite forms a series of thin beds and concretions, mostly in a 30-foot zone of the gypsum and in fine sandstones and shales.

Apparently the two most important areas are the Celestite Hills, about 3 miles west of Cave Springs Wash, and the section just east of the south end of Cave Springs Wash. However, celestite-bearing sediments are exposed over a distance of about 7 miles west of Cottonwood Spring to the Celestite Hills.

The largest celestite bed is approximately 2,100 feet long and about 13 feet thick. Many other celestite bodies are only 1 or 2 feet thick and several feet long, but the majority of the celestite occurs as small lenses and concretions.

An average of three chemical analyses showed about 81 percent $SrSO_4$. The quantity of celestite rock in this area has been estimated at about 300,000 tons. Because of their small size and unfavorable nature, some of the deposits may not have economic importance (*46, pp. 15–21*).

Barstow.—Deposits of strontianite occur 10 miles north of Barstow in the Mud Hills. The two principal deposits, one-half mile apart, are in secs. 20 and 30, T. 11 N., R. 1 W. The strontianite occurs as beds, crosscutting bodies, nodular masses, and concretions in tuffs and clays. At the deposit in sec. 20 two principal zones about 10 and 25 feet thick, separated by about 20 feet of barren clay, contain most of the strontianite. At the other deposit nodular and lenticular beds are distributed vertically through 186 feet of clay at a stratigraphic horizon several hundred feet higher than in the first mentioned deposit. Some investigators have estimated that at least 140,000 tons of strontianite-bearing rock is present, but this is probably a conservative estimate. Small tonnages of strontianite have been produced from both deposits, which are only about 3 miles from the paved road to Barstow, 8 miles away.

Bristol Dry Lake.—Celestite has been found along the south edge of Bristol Dry Lake for 3 miles both east and west of the county road from Amboy to Twenty-nine Palms. Celestite occurs at three horizons to a depth of 1.6 feet in sandy, gypsiferous clay and in thin bedded sand. Strontium is in the sediments below this level and in solution in the waters of the playa, suggesting that the concretions are forming at present. Some of these concretions have been gathered and shipped. No estimates of this resource have been made, but tonnages appear to be significant.

Other occurrences of celestite have been reported (unconfirmed) from the colemanite workings at Borate City in the Calice Mountains and with colemanite at Ryan. A large deposit has been reported at Cadiz Dry Lake.

The Tertiary formations through this general area could contain undiscovered deposits of strontium minerals.

KENTUCKY

LIVINGSTON COUNTY

An occurrence of celestite was reported in the Kentucky-Illinois fluorspar district, 8 miles northwest of Salem, Livingston County, Ky. (*26*).

Celestite was found at a depth of 30 feet in a shaft on the Jameson fluorite prospect. It occurs as a stringer 1 to 2 inches thick in a limestone-calcite breccia. The stringer consisted of small celestite crystals and crystal aggregates lining a narrow fissure. The crystals were distorted and tabular, approximately 1 inch wide and ¼ inch in thickness. The mineral is believed to have been deposited by hydrothermal solutions closely allied to those responsible for deposits of fluorspar in the area.

MICHIGAN

MONROE COUNTY

Dolomites quarried in the area around Scoville and Ida have been found to contain more than 10 percent strontium sulfate occurring as celestite in veins and cavities. It is also found as scattered crystals and masses in the Sylvania sandstone near Rockwood. The Michigan State Geological Survey and the Chemical Engineering Department of the Michigan State College have investigated the mineral. This sandstone is mined for use as glass sand (*22*).

MISSOURI

PERRY AND CAPE GIRARDEAU COUNTIES

Cores from wells drilled in the southeastern corners of both Perry and Cape Girardeau Counties have been found to contain appreciable amounts of celestite. It generally occurs as flat, tabular crystals, light in color and having a satinlike luster. It is associated with a dolomite, probably of the lower Ordivician Joachim formation, at a depth of about 440 feet (*14*).

NEW YORK

SCHOHARIE COUNTY

A deposit of strontianite 2 miles north of Schoharie on the face of Terrace Hill has been worked in the past. It occurs as geodelike masses in a fissure in the limestone. The deposit was worked in a small way through a drift at the base of the cliff, and the strontianite lowered in buckets on a cableway.

Strontianite associated with barite is reported occurring in a limestone east of Schoharie; however, this mineral may be baritocelestite.

Celestite is also common in the Lockport dolomite in Niagara, Monroe, and Wayne Counties, where it occurs in cavities, as fibrous, lamellar, or radiating prismatic crystals. Occurrences have also been reported in Herkimer and Jefferson Counties.

OHIO

OTTAWA COUNTY

One of the world's famous localities for celestite is Strontian Island (in Lake Erie), where beautiful, bluish crystals have been found in limestone.

Original from THE OHIO STATE UNIVERSITY

A small quantity of celestite has been collected by hand at the dolomite plant of United States Gypsum Co. at Genoa. The celestite content of the deposit averages around 3 percent, although during certain operations slightly higher percentages accumulate in the screenings. Analyses of the product indicated that its composition would fall within the following range: Strontium sulfate—94 to 96 percent; calcium sulfate—.5 to 1.5 percent; barium sulfate—2.5 to 4 percent.

Celestite occurs in the Monroe formation in a narrow belt extending from Fremont north to Gypsum on Lake Erie. Small crystals dispersed throughout the formation constitute about 6 percent of the rock.

Masses of relatively pure crystals of celestite occur in the Niagara formation at Clay Center. The mineral occurs as rough, lenticular bodies a few inches to several feet wide, with the long axis usually parallel to the bedding. The celestite zones are of small horizontal extent and seem to occupy solution cavities (*9*). The material, comprising about 3 percent of the rock, could be handpicked.

PENNSYLVANIA

BLAIR COUNTY

A celestite occurrence is reported one-half mile southeast of Bellwood in the Will's Creek formation of upper Silurian age (*37*). The Wills Creek at this locality is 650 feet thick from the top of the Bloomsburg redbeds to the base of the Tonoloway limestone. Celestite occurs in crystalline form 41 feet above the Bloomsburg redbeds in and along the joints, mud cracks, and bedding planes. Above this horizon the crystals are more abundant but are smaller. A vein of fibrous celestite occurs 47 feet above the Bloomsburg. The vein is one-fourth inch thick and is overlain by 5 feet of arenaceous and calcareous material in which disseminated veins and crystals of celestite are found. Fifty-two feet above the Bloomsburg five veins of fibrous celestite averaging one-eighth to one-fourth inch occur in a zone 1 foot thick. Higher in the section, about 70 feet from the base of the formation, five more veins of the fibrous mineral ranging in thickness from one-fourth to five-eighths inch occur.

Another locality for celestite has been reported in a road cut along U.S. 220 about 3½ miles northeast of Bellwood. The celestite occurs as small, pale-blue tabular crystals, occasionally in the form of rosettes, associated with crystallized and fibrous calcite, and in joints and bedding plains in black, shaly material. Celestite has also been reported occurring as faintly bluish, prismatic crystals, measuring almost 1 inch in length, from the Williamsburg formation in central Blair County.

TENNESSEE

FENTRESS COUNTY

Mineral aggregates of celestite, dolomite, and calcite and small quantities of sphalerite, anhydrite, and pyrite occur as vug fillings in the uppermost beds of the Glen Dean limestone, which outcrops along the slopes of Buffalo Cove (*24*). The known vertical range in the Glen Dean limestone is 7 to 20 feet or more downward from the contact with the overlying Pennington shale. Isolated crystals of celestite also occur embedded in the limestone.

In one quarry developed in the area the celestite constituted about 6 percent of the rock. Some of the product was purchased during World War II by Inorganics, Inc., Knoxville. Underground mining might not be practicable because of the weak overlying shale, but open quarries might be developed on the divides between the numerous ravines in the sides of the coves. Beneficiation of the ore yielded a concentrate containing 96 percent $SrSO_4$, with no barium present; however, the cost of beneficiation was prohibitive.

The area is reached by going south 1.6 miles from Jamestown on U.S. Highway No. 28, then west 3 miles on a gravel road and then east on an access road. The Oneida & Western Railroad from Jamestown to Oneida, approximately 40 miles to the northeast, connects at Oneida with the main line of the Southern Railroad.

WARREN COUNTY

Celestite occurs as a soft white crystalline material within chert nodules in a dolomite matrix between Bennett and McCorkle Hollows on the west slope of Ben Lomond Mountain on the Elkins Estate, 5 miles south of McMinnville. Immediately above the ore horizon is a 6-inch bed of thinly laminated shale. The celestite beds, having a maximum thickness of 12 to 18 inches, have been traced for about 1 mile along the hillside. The celestite-bearing chert occurs as irregular masses, small lenses, and nodules in the dolomite matrix. The slope of the hillside changes from fairly steep just below the celestite bed to a more gentle inclination just above it. The slope above the outcrop of the celestite would permit stripping 50 to 100 feet back from the outcrop. This area is estimated to contain about 33,000 tons of 5-percent $SrSO_4$ ore that could be mined by open pit after removal of the overburden.

TEXAS

Strontium minerals (largely celestite) occur in three principal areas in Texas. One of these areas comprises Nolan, Fisher, Coke, and Taylor Counties; the second includes scattered areas throughout the central Texas counties of Somervell, Erath, Comanche, Brown, Mills, Lampasas, Burnet, Williamson, and Travis; the third is in Real and Uvalde Counties (*19; 29*). These deposits have been extensively test-pitted and channel-sampled by the Federal Bureau of Mines and the University of Texas, Bureau of Economic Geology. The deposits have been known since before the turn of the century, and there was a substantial production of low-grade celestite from this area during World War II for use as a substitute for barite in well-drilling muds.

NOLAN, COKE, AND FISHER COUNTIES

The known deposits of celestite (with minor strontianite) in Nolan County are in a narrow belt about 45 miles long extending north into central Fisher County and south into Coke County.

The strata containing the celestite zone consist of soft sands and sandstone, shales, and thin beds of dolomite and dolomitic limestone that comprise the Double Mountain formation of upper Permian age. In the northern part of the district the celestite apparently is restricted to the single horizon of the Claytonville dolomite formation. In the central part of the district the main deposits occur at several horizons within the group of strata 30 to 110 feet below the Claytonville; minor occurrences are found at several levels still lower in the section. The deposits in the southern part of the district are at several horizons, and, because of discontinuity of beds, they have not been positively correlated with the celestite-bearing beds of the central area.

The exposures of the celestite zone which are in the low-lands east of the plains escarpment are disconnected, being sometimes concealed by the Cretaceous overlap, more recent stream and wash sediments, and windblown sand.

The more important celestite deposits (by reason of abundance, grade, and accessibility) occur as replacements in the dolomite and dolomitic limestone, in thin seams and as nodules along bedding planes, and as cementing material in the sandstone.

BROWN, COMANCHE, AND MILLS COUNTIES

The largest and best deposits in this central district are in eastern Brown County, where celestite beds or sheets are associated with, and are at various horizons in, a series of impure limestones, shales, and fine sands believed to represent a phase of the Glen Rose formation. Celestite also occurs in veins, seams, irregular masses, and nodules above and below this bedded zone.

The thickness and quality of individual beds of celestite vary. Beds range from about 2 inches to 1 foot in thickness. Common impurities are limestone and shale, with minor barite, calcite, and iron. Throughout eastern Brown County there are scores of outcrops from which a few hundred to several thousand tons of celestite could be recovered. More than a quarter million tons of celestite-bearing rock, with an average of about 75 percent $SrSO_4$, is indicated in this district.

Celestite occurs as a replacement in impure limestone about 6½ miles north of Blanket in Comanche County and 4 miles east of Zephyr in western Mills County.

Elsewhere in outcropping Glen Rose formations (in which strontium minerals are persistent minor constituents) there are numerous occurrences of celestite: Mount Bonnell in Travis County; at the heads of Lynch and Little Lucy Creeks east of Nix in Lampasas County; along Paluxy River in Somervell County.

TAYLOR COUNTY

Celestite nodules and concretions form a minor percentage of the sandy shales of the Chosa formation around the base of Castle Peak about 7 miles south of Merkel in the western part of the county.

REAL AND UVALDE COUNTIES

Celestite occurs in Glen Rose outcrops in several places in Real and Uvalde Counties, but too little is known of these to judge their importance.

UTAH

It was reported that a commercial deposit of high-grade celestite occurs in Emery County approximately 50 miles southeast of Green River (*1*).

Celestite also occurs as a gangue mineral at the Lead Hill mine about 4 miles east of Salina in Sevier County.

WASHINGTON

SKAGIT COUNTY

A strontium deposit, from which small quantities of celestite and admixed strontianite have been mined intermittently since the First World War, is on the southeast corner of Fidalgo Island in western Skagit County. The town of LaConner is situated about 1 mile to the northeast on the mainland. To reach the strontium deposit it is necessary to go by boat from LaConner through the south end of the Swinomish Slough to the open sound and then west along the south cliffs of Fidalgo Island.

Strontium minerals occupy a shattered zone running northeast and dipping to the northwest. The zone varies between 3 and 4 feet in thickness and the strontium minerals occur in stringers and pods which parallel the strike of the shattered zone (*4*). The country rock sometimes predominates in this zone with the celestite and associated minerals being minor.

The deposit outcrops from tide level to the top of the hill and then can be traced northeastward for a short distance until obscured by the vegetation. Just above high-tide line a tunnel has been driven on the vein. At the top of the hill a trench has been excavated on the vein.

The Fidalgo Island strontium minerals are unusual in that they occur as vein filling in a zone of shattered igneous rock, whereas most strontium minerals are associated very closely with sedimentaries.

FOREIGN DEPOSITS

ARGENTINA

The Argentine Mining Union has reported that Argentina is capable of exporting 1,000 to 3,500 tons of celestite annually, but little is known of the deposits, reserves, or grade of the product.

AUSTRALIA

Veins of celestite are known to occur in a broad shallow watercourse at Fossil Creek about 28 miles northwest of Oodnadatta in the State of South Australia. The numerous veins of celestite are up to one inch in width; however, their longitudinal and vertical extensions are not known. Other celestite-bearing veins may be found by further prospecting (*18*). A celestite sample from this area was analyzed by the South Australia Department of Mines with the following results (*31*):

	Percent
SiO_2	1.04
Al_2O_3	.08
Fe_2O_3	.28
$SrSO_4$	96.54
$CaSO_4$	.58
$BaSO_4$	.24
MgO	.18
H_2O	.39
	99.33

CANADA

Several deposits of celestite of potential economic interest occur in Canada; but production has been sporadic, and output has been small.

Strontianite was found in a vein on the property of Yale Lead and Zinc Mines, Ltd., at Ainsworth, British Columbia, but the deposit has not been developed.

Several occurrences of celestite in eastern Ontario have been examined and the most important is about 5 miles south of Calabogie, Bagot Township, Renfrew County. Celestite occurs as fibrous and friable masses in a dolomite matrix, and the beds are usually a few inches to 1 foot thick although beds as much as 2 to 3 feet thick have been discovered. Some celestite has been recovered from this deposit by open-pit extraction and hand cobbing. The material was ground in a small mill erected at the site and used as a substitute for barite in paint. It was said to contain 15 to 18 percent barite.

In Landsdowne Township, Leeds County, a deposit of what seems to be very pure celestite occurs as a narrow vein in limestone, but no reserves have been proved. Other occurrences of celestite have been reported in Loughborough Township, Frontenac County, and in Fitzroy Township, Carleton County.

Several occurrences of celestite in Nova Scotia and strontianite in Newfoundland have been reported but not investigated.

FRANCE

A vein of celestite reportedly about 16 feet thick is in the Rouet ravine near Condorcet, Department of Drôme (*6*). It is said to occur in a marl, with sphalerite and galena as accessories. Other celestite in the area is said to be associated with barite, calcite, dolomite, and siderite. The deposits have been partly developed, and reserves are reportedly large.

Celestite of potential commercial importance has been reported at Clavellas, Department of Hautes-Alpes, and at St. Geniz, Department of Basses-Alpes.

GERMANY

In the past commercially important production of strontianite has come from veins in marls and beds in dolomites in the region around Hamm and Münster in Westphalia. For many years this was the world's principal source of strontium. Veins in this area are numerous and range in width from 10 inches to 6 feet; they have been mined to a depth of 175 feet, where they thinned. Strontianite also occurs as a component of vein material at Clausthal, Grund, and St. Andreasburg in the Harz and at Braunsdorf in Saxony. A minor occurrence associated with zeolites is reported at Oberschaffhausen, Baden.

Celestite is found at several places in Germany: In sediments at Giershagen, Westphalia; Helmscheid and Obergembeck, Waldeck; in veins at Scharfenberg, Saxony; in marls at Luneberg, Hannover; at Dornburg, Thüringia; and in limestone near Wurzburg, Bavaria.

GREAT BRITAIN

Since World War I Great Britain has been the world's principal supplier of celestite. Both celestite and strontianite are found at numerous places in England and Scotland. Strontium derived its name from the small village of Strontian, Argyllshire, on the west coast of Scotland, where strontianite first was found occurring in veins with galena and barite. However, the most important deposits at present, and probably in future, are those in Gloucestershire and Somerset. Celestite in this area occurs as irregular masses, lenticular bodies, and fracture fillings in the Keuper marl and the Keuper dolomitic conglomerates, both Triassic in age (*12*).

In recent years the most prolific deposits have been those in a narrow belt running south several miles from Cromhall through Yate to Standhawe's Court. Although little information is available on reserves, during the past 80 years over one-half million tons of celestite has been taken from these deposits, and remaining reserves appear to be substantial.

English celestite is relatively pure. Of 29 samples analyzed, the average strontium sulfate content was 91.1 percent. Table 2 shows typical analyses of commercial celestite from three different producing mines in Gloucestershire (*12*).

TABLE 2.—*Analyses of English commercial celestite*

	Yate lawns	The moors	Cowship
$SrSO_4$	98.60	92.10	97.40
$BaSO_4$	.25	.35	.95
$CaSO_4$	.11	nil	.10
$CaCO_3$	.06	4.91	.08
$Fe_2O_3Al_2O_3$	.26	.82	.34
SiO_2	.68	1.30	.04
Undetermined	.04	.52	.09

Formerly many small operators (mostly farmers) recovered small tonnages from open pits in their fields; the pits later were filled and the area farmed again. However, the number of operators has narrowed to a few large producers. One of the largest celestite operations is about 20 miles from Bristol Harbor, where the output is about 6,000 tons annually from an open pit. Production could be more than doubled if the market were available. New operations are believed possible in this area.

INDIA

Celestite occurs at several places in India, but all deposits are minor. One of the more important deposits is in the Trichinopoly district, Madras, South India. The celestite is found in veins and concretions in Cretaceous clays associated with gypsum, barite, calcite, and phosphatic nodules. An estimated million long tons of celestite is reported. After the rains each year celestite-bearing concretions and other rock fragments that have been washed out of the clays are gathered. Therefore, production has been small. The Royal Institute of Science at Bombay has conducted research on the extraction and utilization of this celestite.

Occurrences of minor importance have been known for years in the Kohat district of Northwest Frontier Province and in the upper Sind.

A high-grade deposit of celestite occurs in the Mianwali district, Punjab; the reserves are estimated to total 500,000 tons of celestite averaging 97 percent $SrSO_4$ (*34*).

MEXICO

San Luis Potosi.—Production of celestite began in Mexico January 1941 at the Providencia mine, nearly ½ mile from the village of Villa de la Paz, 7½ miles by road from Matehuala, the terminal of a branch of the Mexican National Railroad that connects at Vanegas with the main line between Mexico City and Laredo. Vanegas is 353 miles south of Laredo and 447 miles north of Mexico City.

The first producer of celestite was Leo V. Naudin (from property owned by Nester A. Barba). By 1943 Mexican output of strontium minerals had reached 6,000 short tons annually, mostly from San Luis Potosi.

The Providencia mine has been worked nearly 70 years as a gold-silver operation. Celestite was discovered when the property was first developed, but it was not considered important until World War II, when English supplies were interrupted. This mine has been producing more or less continuously since 1941. The extensive workings of the mine have facilitated exploration of the celestite veins. The celestite is packed by muleback to La Paz, and from there to Matehuala by the Ferrocarril de Matehuala (Matehuala Railroad) where it is reloaded in larger railway cars for shipment to the United States. Some is carried overland through Laredo and some to Tampico to be shipped by boat. Output ranges from 400 to 700 tons per month.

All veins in the district run east-west and are of the fissure type. Veins in the eastern part of the property are worked principally for silver, but to the west are worked for copper. There are two main celestite veins; the principal one is the Boca Mina and the second, about 328 feet distant and parallel to it, is the Arroyo. Many celestite stringers run into these veins. Most of the country rock in the district is limestone, although at Providencia it is mainly brecciated shale.

Coahuila.—In the Sierra Mojada mine in Coahuila the minerals strontianite and celestite occur as vein fillings or gangue in lead veins. The primary strontium mineral probably was celestite, part of which has been altered to strontianite.

Sierra Mojada was discovered about 1887 and has been worked almost continuously since that time, producing about 6 million tons of various types of ores, chiefly oxidized lead silver, limestone impregnated with copper and silver, and oxidized zinc.

A new lead ore body, the Suiza, different from the usual type, was discovered about 1927. Silver values are much lower, lead content is much higher, iron oxides are virtually absent, and the strontium minerals, celestite and strontianite, occur as gangue minerals, whereas they are absent in the other lead ore bodies.

The original strontium content of the ore body was probably 5 to 10 percent strontium sulfate. At the time of the discovery of strontium at Sierra Mojada, the possibility of its commercial exploitation was investigated. Because of restricted markets, unsatisfactory price quotations, and cost of separating it from the lead ores, no strontium was produced for sale; it was shipped to the smelter as part of the lead ore gangue.

Some of the higher grade strontianite and lower grade lead pockets were left on the walls of the stopes. This, along with strontianite that was sorted out of the lead and left in the fill, constitutes the strontianite reserve at Sierra Mojada. It is difficult to estimate what now remains, but it could be several thousand tons. To recover the strontium minerals it would be necessary to reopen the abandoned stopes and restore the levels and shaft. The ore body containing the strontium minerals was mined to where it was lost on a large fault zone of about 300 feet displacement. Further exploration, now in progress, to find strontium-bearing pockets or veins is encouraging and could lead to additional mines being developed.

The San Augustin mine in Sierra de la Paila is one of the principal current suppliers of celestite. This mine is operated only for celestite, and the grade is relatively high, consistently near 95 percent $SrSO_4$. The recent production rate has been more than 200 tons annually. Reserves are believed to be adequate for several years. The ore is mined by simple methods and beneficiated by hand jigging. The lump material so obtained is shipped by rail through Laredo.

An appreciable quantity of celestite occurs in the limestone deposits being mined near Mexico City for use in one of the cement plants. The celestite is said to occur in irregular seams and beds and would require careful sorting to secure a commercial grade. It was estimated that one car a week might be secured from this source, but no known effort has been made to recover it.

Other reported occurrences of strontium minerals in Mexico seem to be merely prospects on which little or no exploratory work has been performed. At this time no statement as to the possibilities of production from these properties can be made, and only field examinations by competent engineers can determine their potentialities. There are several deposits from which substantial tonnages of adequate material could be had in an emergency.

POLAND

Detailed information on strontium mineral deposits is lacking; however, it has been reported that known celestite reserves are adequate for present uses, mainly manufacture of small amounts of strontium chemicals.

SICILY

Celestite occurs in relative abundance in association with the extensive sulfur deposits in Sicily, principally in the areas around Girgenti and Caltanissetta. Irregular masses of crystalline celestite occur in fissures in sulfur, limestone, aragonite, and gypsum. Considerable quantities have been recovered in the past, mostly for export to Germany, but the cost of recovery and transportation is relatively high.

SPAIN

The United States Commercial Co. purchased several thousand tons of celestite from Spain during World War II under a preclusive buying agreement. The deposit from which this material was derived is the Montevive mine about 15 kilometers south of Granada. The celestite was transported by trucks to Gavia 5 miles away; by rail from Gavia to the port of Montril. The deposit is on a hill about 2 miles in diameter consisting essentially of flat-lying sedimentary beds of limestone with some gypsum and barite. Celestite beds of varying thickness seem to have been precipitated with Miocene lake sediments. Other possible sources are associated hot springs and fumaroles. Unconfirmed estimates of reserves run as high as several million tons of potential "ore." It is estimated that about 3,000 tons of celestite per month could be produced from currently developed workings.

TUNISIA

Both celestite and strontianite occur as gangue material, along with fluorite, calcite, and barite, in many lead-zinc veins in Tunisia. A substantial tonnage can be expected from this source, but the supply is erratic.

U.S.S.R.

Strontium minerals have been found at many places in U.S.S.R. and other countries behind the Iron Curtain, and there is no reason to believe that available supplies are inadequate. The following occurrences have been mentioned: Zaunguz Plateau in the Karakum Desert; in the lower Muschelkalk and Rot formations near Jena; the Permian deposits of Bashkir; and in the caprocks of the Romny and Isachkov salt domes. Large masses of celestite are reportedly found in the Penega River area of Archangel Province; the deposits resemble those found in Sicily, and the celestite is reportedly of excellent quality.

CHAPTER 3. MINING, MILLING AND PROCESSING

MINING AND MILLING

As in all mining operations, the nature of the individual deposit and the rate and scale of extraction influence selection of the mining method. Because of the small tonnage requirements, strontium minerals have been produced only by simple methods and on a small scale.

UNITED STATES

In the United States strontium ore is selectively mined either from surface outcropping beds by simple open pit methods or from veins by short adits and drifts. Mining is followed by hand picking, rough sorting, and loading.

Power shovels were used to strip the thin cover overlying the shallow, flat beds of celestite that have been worked in Texas and tractor-drawn plows used to break up the celestite. At some operations the celestite has been simply pried out of exposed ledges with handtools.

In California the deposit near Westmoreland has been developed by opencuts in the side of a hill. The ore body is drilled and blasted, and the ore is carried by mine cars to bins from which it is loaded into trucks for transport to the railhead at Westmoreland.

One of the most serious deterents to development of domestic deposits is the difficulty in concentrating the strontium minerals to an acceptable grade. During World War II several methods were used in an attempt to produce a Chemical-grade celestite from low-grade Texas ores. Classification and tabling, flotation, and dense medium methods were tried. Bureau of Mines methods combined classification, tabling, and froth flotation to produce from composite samples a concentrate running 92.5 to 93.5 percent $SrSO_4$ and from individual samples a concentrate running as high as 95.8 percent $SrSO_4$.

Mineral-dressing investigations were also conducted on representative medium- to low-grade samples of celestite from Brown County, Tex. Tests were made on a composite sample from five properties. Zeolite-softened water was used in the grinding and flotation processes. A portion of the sample was crushed to minus-20-mesh, deslimed, and classified in a constriction-plate hydraulic classifier. The coarse, classified products were tabled to make concentrate, middling, and tailing. The middling was crushed to minus-48-mesh and retabled with the fine, classified products. Table concentrate and middling were combined and reconcentrated by flotation. The use of quebracho plus copper sulfate was found most effective in depressing carbonate gangue. A recovery of 73.8 percent of celestite in the feed was made; but, what is more important, a flotation concentrate containing 91.5 percent strontium sulfate, 5.0 percent barium sulfate, 0.7 percent silica, and 0.53 percent carbon dioxide was obtained. In this process the barite was as readily flotable as the celestite. A pilot-plant confirmation of the laboratory results was conducted as follows (*29*):

> A sample of 5 tons was crushed in jaw crusher and rolls to minus-20-mesh and then mixed. The crushed ore was fed at the rate of 60 pounds an hour to a double screw spiral classifier, where water was added and the pulp was deslimed. Each spiral was 5.5 inches in diameter, 64 inches long, and was operated at 13 r.p.m. The deslimed sand, without further classification, went to a No. 15 Deister laboratory table, where some calcite and silica were removed. It would have been desirable to classify the table feed, but available facilities would not permit this additional operation. The table concentrate was dewatered in an 8 inch spiral classifier 36 inches long operated at 3 r.p.m.
>
> The dewatered table concentrate went to a 19- by 36-inch ball mill loaded with 275 pounds of 2- to 3-inch pebbles. The ball-mill speed was 30 r.p.m. Soda ash and zeolite-softened water were introduced with the feed at the head of the mill. The pulp consistency in the mill was maintained at 41 percent solids. The ball-mill discharge was classified in a 12-inch Akins classifier 60 inches long, operated at 20 r.p.m. The classifier overflow had a pulp density of 22 to 24 percent solids, which provided a flotation feed about 95 percent minus-200-mesh. Overflow from the classifier was laundered to the conditioners, where Quebracho and copper sulfate were added in that order. The reagent feeders were of the constant-head, siphon type. The conditioned pulp was floated in two 6-cell banks of Denver No. 5 laboratory cells. One bank of cells was used for roughing and the other for cleaning. Oleic acid and other collecting agents were added to the pulp entering the rougher cells. No additional reagents were necessary in the cleaner cells. The middling from the cleaner bank was pumped back to the conditioners and recirculated.
>
> A concentrate containing 92.5 percent strontium sulfate, 5.2 percent barium sulfate, 0.5 percent silica, and 0.79 percent carbon dioxide was produced, with a recovery of 56.9 percent of the celestite. This was a somewhat smaller recovery than in the batch test, but the grade of concentrate was higher.
>
> In order to increase the recovery of celestite, the use of auxiliary frothers with some collecting power was investigated. The two reagents used were organic

sulfates K-480 and X-1, both products of the Emulsol Corp., Chicago, Ill. The use of frothers permitted greater flotation and gave a lighter, less flocculated froth. Most results were equal to or superior to those obtained with the oleic acid alone.

The results obtained with the two frothers were substantially identical. In a second test in which reagent K-480 was used, a recovery of 66.5 percent of the celestite was effected in a concentrate containing 93.5 percent strontium sulfate, 4.5 percent barium sulfate, 0.3 percent silica and 0.82 percent carbon dioxide. This represented the best grade and recovery obtained on the sample.

Figure 6 is a flow diagram of the pilot-plant test.

FOREIGN

MEXICO

In Mexico (San Luis Potosi) the celestite occurs on the hanging walls of a gold-silver-lead vein, with a number of concomitant stringers running into it. This celestite has been mined by hand. Special care is exercised in blasting to prevent the mineral from becoming contaminated with the wall material. To this end small charges of dynamite are placed in large drill holes, so that the ore stays in place after blasting, thus avoiding contamination with waste material. The ore is sacked at the face and carried to the surface by men. When the ore is not broken in mining, the cleaning is accomplished by hand sorting, as it is comparatively easy to remove large chunks of calcite or other pieces of waste. However, at times the ore is badly shattered, and it is then necessary to screen all the material as it comes from the mine. The minus one-half inch material is hand-cleaned and again sized on a one-eighth screen. The plus product is hand-jigged to remove the waste and is then mixed with high-grade ore.

The celestite being mined in Coahuila is produced by similar methods.

ENGLAND

In England the celestite masses, located by probing the soil with long rods, are mined by open pit methods. The pits rarely go deeper than 20 or 30 feet. The celestite lumps formerly were hand cobbed and trimmed, carted to Yate or other stations on the Midland Railway, taken to the harbor at Bristol, and loaded on ships for export. However, in the past few years gravity-concentration equipment has been installed at the English deposits. The celestite now is reduced in a jaw crusher to about 2.5 inches and heated in a rotary, oil-fired drier with a forced-hot-air draft, that both dries the mineral and blows away some of the adhering clay and dirt. It is then further crushed, ground, air-floated, and finally bagged for shipment.

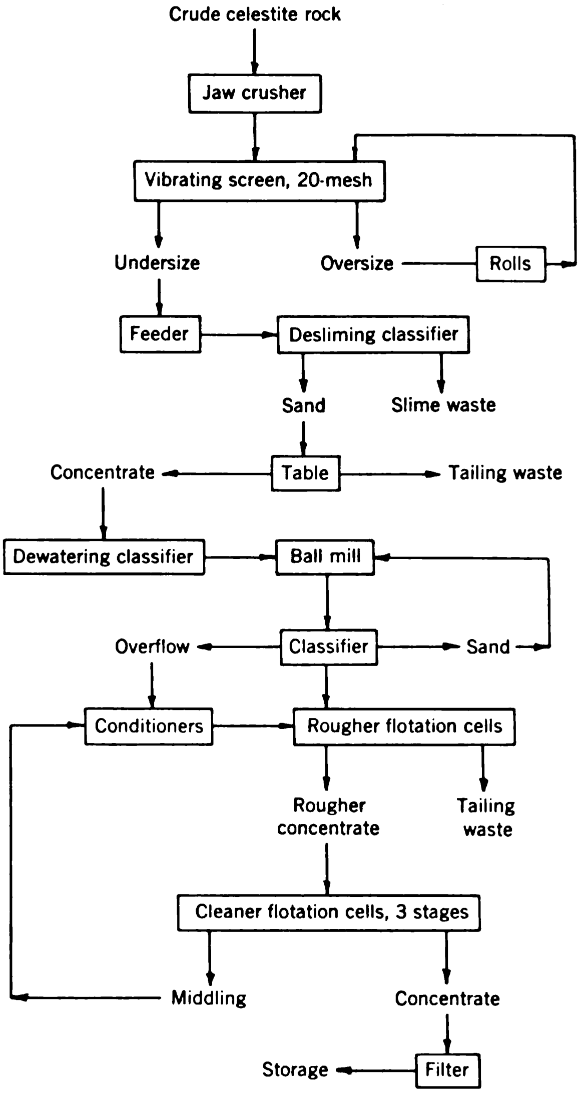


FIGURE 6.—Flowsheet of composite sample for pilot-plant tests, Brown County, Tex., celestite ore.

GERMANY

Deposits of strontianite in Germany have been mined on a small scale, usually by overhead stoping methods. Run-of-mine material averaging about 15 percent strontianite was concentrated at the surface by mechanical washing and hand sorting. A lump product running about 85 percent strontium carbonate was obtained.

SPAIN

Mining at the Montevive Mine in Spain was by hand in open pits, and the only beneficiation was by hand picking.

CHEMICAL PROCESSING

As the bulk of the strontium consumed is in the chemical rather than the mineral form, it is necessary to convert the raw material to one of several strontium compounds. Many methods have been patented and used for the conversion of strontium minerals to strontium chemicals. The two methods most commonly used in recent years are: (1) The soda ash process, in which finely powdered celestite is digested in a hot soda ash solution, yielding the less soluble strontium carbonate, which is in turn treated with the appropriate acid to make the desired salt; and (2) the calcining process, in which finely powdered coal is burned with celestite, producing a soluble strontium sulfide, which is leached from the clinker with water, and the carbonate may be formed by treating the solution with carbon dioxide.

SODA ASH PROCESS

In the soda ash process celestite is crushed to about one-fourth inch (if received in lump), dried in an oil-fired rotary kiln, and finely ground to about 325-mesh to increase its reactivity. The ground celestite is mixed with sodium carbonate solution (about 10 percent), agitated, and heated in reactor vessels to precipitate strontium carbonate. The resulting slurry is filtered on a rotary drum filter to separate the sodium sulfate liquor. The resulting strontium carbonate filter cake is then treated with reagents in purifying tanks to dissolve barium and calcium salts and filtered again to remove these impurities. The resulting filter cake is then dried in a tunnel drier, ground in a micropulverizer, and either packaged for sale or used as the intermediate product in the manufacture of other strontium salts (*28*).

Strontianite is easier to convert to strontium salts because of its solubility in acids. For example, the nitrate can be prepared simply by treating the strontianite with nitric acid, filtering off the insoluble residue, and evaporating to the crystallization point.

CALCINING PROCESS

This method, which has been employed for many years, involves calcining finely powdered coal and celestite (325-mesh) in a rotary kiln, thereby reducing the insoluble strontium sulfate to the water soluble strontium sulfide. The furnace clinker so obtained is leached with water, the insoluble impurities are removed by filtration, and the carbonate is made by treating the sulfide solution with carbon dioxide. Other strontium salts can be prepared either directly from the sulfide solution or by treating the carbonate with the acid of the desired salt. Preparation of pure strontium compounds from aqueous solutions of the sulfide is difficult because of contamination with sulfur compounds.

Strontianite can also be reduced with coal, producing strontium oxide, which, on treatment wih water, forms strontium hydroxide. Because of the presence of calcium in most strontianite, it is desirable to use celestite for producing pure strontium compounds.

EFFICIENCIES

Theoretically by empirical calculation it requires approximately 1.25 tons of strontium sulfate (100 percent pure) to produce 1 ton of strontium carbonate with 100-percent efficiency. Commercial plant efficiencies are about 80 percent, and commercial celestite averages about 94 percent $SrSO_4$. Applying these factors, it would require about 1.5 tons of celestite per ton of strontium carbonate, with a resulting loss of a little less than 20 percent on a chemical basis.

Conversion of the carbonate to other compounds and the preparation of high-purity strontium compounds involve additional processing steps and consequent losses. For example, in conversion of crude strontium nitrate to high-purity carbonate about 80 percent of theoretical recovery is achieved (theoretically about 211 pounds of crude nitrate yields about 147 pounds of high-purity carbonate). Subsequently converting this strontium carbonate to other high-purity compounds involves three or four additional steps, each of which may result in a loss of about 10 percent. Conversion of crude nitrate to high-purity peroxide usually involves about four steps: (1) Crude nitrate to the carbonate with about 80-percent theoretical recovery; (2) carbonate reduced to oxide with about 90-percent theoretical recovery; (3) oxide hydrated to strontium hydrate with about 90-percent theoretical recovery; and (4) hydrate reacted with peroxide to form the strontium peroxide with about 90-percent theoretical recovery.

PREPARATION OF SALTS

Most strontium salts can be made by treating the carbonate or the sulfide solution with the desired acid, such as oxalic, stearic, tartaric, chloric, nitric, or bromic. However, many methods have been suggested and patented for preparing various strontium compounds and for preparing high-purity strontium salts from the crude or commercial strontium compounds. The purity required and the economics of individual processes are the determining factors in selection of a process.

Commercial strontium hydroxide can be made by first preparing a strontium black ash, that is, calcining finely ground celestite and coal. Steam then is blown through the mixture until the resulting liquor has reached predetermined density. It is allowed to settle, and the hot liquid is treated in tanks with caustic soda and allowed to crystallize.

The hydroxide also is made by reacting strontium chloride and caustic soda to form strontium hydroxide crystals. The crystals are separated from the liquor by centrifuging and either dehydrated or packaged directly.

Other processes suggested for preparation of the hydroxide are: Roasting ground celestite, coal, and brown iron ore and leaching the mass to produce a ferrous sulfide and strontium hydroxide; interaction of strontium chloride and barium hydrate and fractional crystallization or the action of barium hydrate and strontium sulfide; and heating strontianite with superheated steam and calcining to form CO_2 and strontium oxide, which can be hydrated. Another process involves blowing air heated to 100° F. through a mixture of manganese dioxide and strontium sulfide.

By reacting purified strontium carbonate filter cake with hydrochloric acid strontium chloride is formed. The resulting slurry is filtered and the filtrate evaporated to crystals in a single effect or open-pan evaporator. The crystals are then ground and packaged.

Strontium oxalate and tartrate may be formed by reacting strontium carbonate with oxalic or tartaric acid; strontium stearate is made by reacting strontium hydroxide with stearic acid.

The following reaction has been investigated in detail:

$$SrSO_4 + CaCl_2 \rightarrow SrCl_2 + CaSO_4,$$

$$SrSO_4 + Ca(NO_3)_2 \rightarrow Sr(NO_3)_2 + CaSO_4.$$

These reactions may be driven nearly to completion in either direction by controlling the water concentration and molar ratio of the reactants. In dilute aqueous solutions the reactions proceed from right to left quickly even at room temperature. The temperature affects the speed of the reactions. In concentrated aqueous mediums the reactions proceed from left to right to give 95-percent conversions in 24 hours at 150° C. The effects of (1) time, (2) temperature, (3) molar ratio of reactants, (4) water content in reactants, and (5) fusing and the approach to the equilibrium point were determined for the above reactions in aqueous solutions. At the end of the reaction the chlorides or nitrates were separated, using organic solvents (principally pure and aqueous methanol) (*12*). It has been suggested that this may be a commercial process.

PREPARATION OF STRONTIUM METAL

Strontium metal is prepared by thermal reduction of strontium oxide and aluminum metal, subsequent distillation under high vacuum, and condensation of the metallic strontium on a cooled electrode. This method yields a product containing over 99 percent strontium. The metal can also be produced by electrolysis of a fused bath of strontium chloride and ammonium or potassium chloride.

The following is a partial list of patents dealing with the preparation of strontium metal:

French Patent 32,645 (1926).
French Patent 35,177 (1928).
French Patent 676,248 (1929).
British Patent 318,599 (in lead alloys).
British Patent 323,718 (1928).
British Patent 323,766 (1928).
United States Patent 1,797,131 (1931).
United States Patent 1,826,733 (1931).
Netherlands Patent 27,019 (1932).
British Patent 403,120 (1932) (in lead alloys).
French Patent 743,123 (1933).
French Patent 755,875 (1933).
British Patent 408,819 (1934).
German Patent 602,888 (1934).
British Patent 439,204 (1935).
British Patent 440,139 (1935).

THERMAL METHODS

Processes used for preparing barium and calcium metal are applicable to strontium-metal production. The strontium oxide is reduced by mixing finely ground material with powdered aluminum and heating in an evacuated iron tube for 4 hours at 1,000° C. Metal of 99.4-percent purity has been recovered as a crust with a yield of 75 percent. Strontium oxide can be heated with silicon at 1,200° C. in an evacuated steel tube, with the metal condensing in the cooler part of the tube.

According to Thorpe's Dictionary of Applied Chemistry Supplement (vol. II, 1935), high-purity strontium metal was prepared by Danner in the early 1920's by first partly converting pure strontium oxide to peroxide and reducing the oxides by mixing them with coarse aluminum and then striking an arc into the mass. The cold, fused mass was ground and the fine material screened off; the remaining metal was sealed in a distillation apparatus. The latter was evacuated as soon as possible. When the pressure reached 10^{-4} mm., the temperature was raised to 950° C. and the strontium distilled off. Other methods for preparing strontium metal are outlined by Thorpe.

ELECTROLYTIC METHODS

Strontium amalgam can be made from aqueous solution, but it has not yet been found feasible to recover the pure metal. However, strontium has been prepared by electrolysis of a fused mixture containing 84 percent strontium chloride and 16 percent potassium chloride in a graphite crucible with cooling of the upper cathodic space.

Strontium metal is rather difficult to prepare and is relatively expensive. Molten strontium readily forms oxides, hydrides, nitrides, and carbides, and this makes melting and pouring difficult. The metal reacts with virtually all of the common gases, such as oxygen, hydrogen, nitrogen, and carbon dioxide, and it is impractical to carry on melting and pouring operations, except in inert atmospheres of argon or helium.

PREPARATION OF ALLOYS

Only a relatively few of the possible strontium alloys have been prepared and studied, and these were mostly relatively impure. Very little information is found in the literature on the methods used to prepare these alloys, type of crucibles, current efficiencies, compositions of the electrolytes, percentages of strontium that can be deposited in the alloy, types of tests, data on properties, or other information.

It seems that the electrolytic is the easiest and most convenient method of preparing the binary alloys of strontium. Most of even the binary systems involving strontium have been examined only incompletely.

Several methods of producing alloys have been discussed (*5*).

Strontium-zinc and strontium-cadmium have been prepared by heating a mixture of the anhydrous chlorides of these metals with sodium. A method of preparing alkali-earth alloys of lead, aluminum, copper, etc., has been suggested; and, using this method, sodium-lead alloys were heated with the strontium chloride to obtain a lead-strontium alloy. Another method of preparing lead-strontium (and other alkali-earth metal alloys) has been patented by Kroll. In this method the metallic lead is heated with an alkaline earth carbide.

Early attempts to use electrolytic methods for preparing strontium alloys were not successful. Mechanical failures of the crucibles and contamination of the alloy were the major problems. Inefficiency because of the high melting point of the chloride was a problem, and when other alkali-earth halides were added to reduce this melting point contamination or rapid volatilization resulted.

One of the most commonly produced alloys is copper-strontium, for use as a hardening agent in castings and to free them from blowholes. This alloy is made by adding metallic strontium to the melt or by electrolysis of fused strontium chloride or other strontium salt, using a molten-copper cathode. A lead-strontium-tin alloy is made in much the same way for use in storage-battery anodes. Other alloys, such as strontium-aluminum (containing up to 50 percent strontium), strontium-lead (containing up to 10 percent Sr), and strontium-cadmium (containing up to 5 percent strontium) have been made and used.

CHAPTER 4. DOMESTIC SUPPLY REQUIREMENTS POSITION

Since the end of World War I United States supplies of strontium minerals have been largely of foreign origin. Production from domestic deposits, even during World War II, was sporadic, and output was small. Domestic production in the past few years has been almost negligible—in some years none and in other years about 7,000 tons. A substantial import of Spanish celestite during the few years after World War II was the delayed delivery of material purchased under a preclusive buying agreement concluded with Spain during the war. Nearly all current supplies of Chemical-grade celestite are imported from England and Mexico.

Requirements for celestite and strontium compounds usually are small and erratic, ranging in the past decade from a few thousand tons to about 14 thousand.

DOMESTIC SUPPLY

Small quantities of both celestite and strontianite were produced during World War I. Table 3 shows domestic production during the years 1916 to 1918.

TABLE 3.—*Strontium-mineral production in the United States, 1916–18 (20)*

[In short tons]

Year	Celestite	Strontianite	Total
1916	240	10	250
1917	3, 630	405	4, 035
1918	----------	400	400

After World War I domestic production was discontinued because of competition from foreign sources, except that, beginning in the late 1930's, low-grade celestite was produced in Texas for use as a substitute for barite. In 1940 several domestic producers of Chemical-grade celestite resumed production on a small scale. Table 4 shows the available data on production to date.

DOMESTIC REQUIREMENTS

Requirements for strontium minerals and the various compounds are small and erratic. In the past decade requirements have varied from a few thousand to about 14,000 tons per year. The major portion of the domestic requirement for strontium is for use in essential or important applications, such as tracer bullets and signal and warning flares by the military establishment and warning flares and fusees by railroads and truckers. During wartime the requirements for strontium compounds increase because of its military uses.

TABLE 4.—*Domestic production of strontium minerals, 1940–56*

Year	Quantity produced (short tons)	Value
1940	350	------------
1941	4, 724	$69, 054
1942	4, 041	55, 529
1943	7, 566	114, 526
1944	3, 005	48, 165
1945	2, 784	27, 840
1946	243	3, 726
1947–52	------------	------------
1953	50	1, 000
1954	12	300
1955	177	4, 425
1956	4, 040	77, 160

PRODUCERS OF STRONTIUM MINERALS, COMPOUNDS, AND ALLOYS

During the past 5 years most domestic production of strontium minerals has been in California and Washington. In 1955 the only producer was Gene De Zan, from a deposit near Ludlow, San Bernardino County, Calif. In 1956, in addition to the production from the De Zan deposit, Pan Chemical Co. produced a small quantity of strontium minerals from its operation near Fish Creek, Plaster City, San Diego County, Calif. Manufacturer's Mineral Co., P.O. Box 3543, Seattle 24, Wash., reported production from its deposit near La Conner, Skagit County, Wash.

Imported strontium minerals are converted to the various compounds by the following firms: E. I. du Pont de Nemours & Co. at Grasselli, N. J.; Foote Mineral Company, Philadelphia, Pa.; and occasionally Barium & Chemical Corp., Willoughby, Ohio. Barium Products, Ltd., Modesto, Calif., and Pan Chemical Co. at its Los Angeles plant convert small quantities of locally produced celestite to strontium compounds.

Strontium metal is produced in the United States by King Laboratories, Inc., Syracuse, N. Y., and has been produced in the past by Cooper Metallurgical Associates, Cleveland, Ohio; however, only small quantities are made. Metal Hydrides, Inc., Beverly, Mass., produces small quantities of strontium hydride.

POTENTIAL DOMESTIC OUTPUT

The large reserves and widespread distribution of domestic deposits would show that technically, if not economically, all domestic requirements could be filled from domestic sources. A large tonnage (probably all of the expected peacetime or emergency requirements) of celestite probably could be selectively mined from the numerous domestic deposits and handpicked or otherwise beneficiated to meet Chemical-grade specifications. Development of a substantial domestic production has been economically impractical, except for a few small operators in the Far West, who occasionally produce a small tonnage to satisfy local needs for strontium minerals in the caustic soda industry or for strontium-compounds manufacture.

FOREIGN TRADE

The foreign trade picture has changed several times since the years before World War I, when Germany was the world's leading supplier of strontium chemicals. During that war, when German supplies were cut off, imported English celestite sustained the newly established domestic strontium-chemical industry until the embargo of 1917, which prohibited export of strontium compounds and minerals from England. This embargo tended to stimulate domestic production. With entry of the United States into the war the embargo was lifted, and English celestite again flowed into this country. Between the two World Wars the United Kingdom was almost the sole supplier of strontium minerals to the United States (except for occasional small shipments from Tunisia), and nearly all United States requirements for strontium chemicals were met by domestic firms that converted imported strontium minerals to these chemicals. During World War II, when shipments from United Kingdom were threatened, a source of raw materials was developed in Mexico, and that nation has become increasingly important as a shipper of strontium minerals to the United States. A substantial tonnage of celestite was imported into the United States from Spain in 1942–49. This material was purchased under a preclusive buying agreement concluded with Spain during the war and on which delivery could not be made until after the war.

No imports of strontium chemicals were reported in 1957; however, in 1956 strontium compounds were imported from Italy and the United Kingdom.

Imports of strontium minerals and of the compounds strontium carbonate, nitrate, and oxide, during the period 1925–57, are listed in table 5.

TABLE 5.—*Imports (for consumption) of strontium minerals and compounds into the United States, 1925–57*

Year	Strontianite and celestite		Strontium nitrate		Strontium carbonate, precipitated		Strontium oxide	
	Pounds	Value	Pounds	Value	Pounds	Value	Pounds	Value
1925	2,264,303	$22,082	2,467,011	$137,266	94,635	$3,065	665	$120
1926	4,399,142	58,159	1,027,248	56,643	50	11	6,604	623
1927	2,711,468	58,711	1,509,350	88,244	12,998	2,428	----------	----------
1928	1,517,801	31,157	1,767,550	99,579	92,908	5,584	2,205	241
1929	1,945,577	45,505	2,569,407	145,330	61,138	5,157	2,205	241
1930	440,924	10,459	1,678,886	92,166	33,978	2,182	----------	----------
1931	260	123	1,701,750	80,889	29,452	2,022	11,252	520
1932	11,685	276	438,931	18,699	30,550	2,211	----------	----------
1933	2,426,493	8,457	532,835	23,744	10,073	850	595	115
1934	2,500,411	9,218	237,105	13,796	28,416	3,284	2,204	469
1935	2,674,094	11,595	277,548	15,716	21,828	2,641	----------	----------
1936	3,880,302	14,537	694,696	39,820	[1] 52,311	6,056	(2)	----------
1937	5,636,570	20,877	609,448	40,243	[1] 44,579	4,610	(2)	----------
1938	552,868	2,824	364,362	23,921	[1] 82,859	8,502	(2)	----------
1939	5,645,935	23,136	479,933	32,060	[1] 23,136	2,811	(2)	----------
1940	5,502,029	28,686	----------	----------	----------	----------	----------	----------
1941	8,586,741	66,271	----------	----------	[1] 4,480	646	(2)	----------
1942	20,716,072	144,848	----------	----------	----------	----------	----------	----------
1943	33,761,355	249,580	----------	----------	----------	----------	----------	----------
1944	11,586,147	86,419	----------	----------	[1] 100	97	(2)	----------
1945	7,382,098	50,616	----------	----------	----------	----------	----------	----------
1946	9,014,287	66,198	----------	----------	----------	----------	----------	----------
1947	28,233,615	242,584	----------	----------	[1] 29,680	2,086	(2)	----------
1948	43,541,260	558,709	----------	----------	[1] 2,388	189	(2)	----------
1949	18,768,328	176,685	----------	----------	[1] 44,267	5,506	(2)	----------
1950	17,260,364	142,213	22,741	1,108	[1] 13,440	2,268	(2)	----------
1951	28,087,055	304,504	----------	----------	----------	----------	----------	----------
1952	19,033,372	186,326	----------	----------	----------	----------	----------	----------
1953	13,794,772	123,846	(3)	10	[1] 16,313	11,322	(2)	----------
1954	6,581,354	53,284	----------	----------	[1] 6,614	750	(2)	----------
1955	12,249,065	128,181	----------	----------	[1] 6,616	1,064	(2)	----------
1956	18,878,418	191,547	----------	----------	[1] 4,820	900	(2)	----------
1957	13,050,950	130,731	----------	----------	----------	----------	----------	----------

[1] Includes oxide, if any.

[2] Imports, if any, included with strontium carbonate.

[3] Less than 1 pound.

Since 1935 strontium minerals have been imported from Canada, Germany, Mexico, Spain, Tunisia, and the United Kingdom. The tonnage of these imports and their value appear in table 6.

The United States exports some strontium compounds each year, mostly to neighboring countries in North and South America.

Since January 1946 exports of strontium compounds have not been separately classified by the Bureau of Census, therefore official export data are not available. During the war years (1942–45), however, exports were tabulated, and a summary by countries of destination can be found in table 7. Some of the exports, primarily those to the U.S.S.R. and Algeria, were made under lend-lease agreements.

TABLE 6.—*Imports (for consumption) of strontium minerals into the United States, 1935–57, by countries of origin*

[Bureau of the Census]

Country	1935		1936		1937		1938		1939	
	Short tons	Value	Short tons	Value	Short tons	Value	Short tons	Value	Short tons	Value
Germany	1	$193	(1)	$81	(1)	$54	(1)	$23	(1)	$11
United Kingdom	1,336	11,402	1,940	14,456	2,818	20,823	270	2,603	2,812	22,830
Tunisia							6	198	11	295
Total	1,337	11,592	1,940	14,537	2,818	20,877	276	2,824	2,823	23,136

Country	1940		1941		1942		1943		1944	
	Short tons	Value	Short tons	Value	Short tons	Value	Short tons	Value	Short tons	Value
United Kingdom	2,729	$28,406	3,306	$50,880	2,682	$36,917	1,367	$21,347	(1)	
Tunisia	22	280								
Mexico			987	15,391	6,201	67,789	11,060	148,233	3,170	$38,191
Spain					1,475	40,142	4,454	80,000	2,622	47,576
Total	2,751	28,686	4,293	66,271	10,358	144,848	16,881	249,580	5,792	85,767

Country	1945		1946		1947		1948		1949	
	Short tons	Value	Short tons	Value	Short tons	Value	Short tons	Value	Short tons	Value
United Kingdom			2,530	$42,033	4,344	$74,383	6,043	$103,428	4,904	$86,378
Mexico	3,016	$38,365	1,977	24,165	3,937	57,317	1,114	14,963	1,158	14,690
Spain	675	12,251			5,836	110,884	14,614	440,318	3,263	74,829
Canada									59	788
Total	3,691	50,616	4,507	66,198	14,117	242,584	21,771	558,709	9,384	176,685

Country	1950		1951		1952		1953	
	Short tons	Value	Short tons	Value	Short tons	Value	Short tons	Value
United Kingdom	6,655	$118,303	11,972	$280,392	8,161	$168,849	4,413	$93,077
Mexico	1,975	23,910	2,034	23,730	1,297	16,870	2,441	30,248
Canada			38	382	59	607	43	521
Total	8,630	142,213	14,044	304,504	9,517	186,326	6,897	123,846

Country	1954		1955		1956		1957	
	Short tons	Value	Short tons	Value	Short tons	Value	Short tons	Value
United Kingdom	1,385	$28,397	4,053	$100,781	7,119	$161,676	4,624	$106,499
Mexico	1,906	24,887	2,072	27,400	2,313	28,225	1,896	22,911
Italy					7	1,646	5	1,321
Total	3,291	53,284	6,125	128,181	9,439	191,547	6,525	130,731

[1] Less than 1 ton.

TABLE 7.—*U.S. exports of strontium compounds, by country of destination, 1942–45*

(In pounds)

[Bureau of the Census]

Country of destination	1942	1943	1944	1945
North America:				
Canada	663, 834	569, 479	551, 223	422, 152
Costa Rica		58	100	22
Cuba	282	231	53	118
Dominican Republic		88	50	666
El Salvador		25	40	100
Guatemala		1		
Haiti		2	50	100
Honduras	102			30
Mexico	746	2, 740	29, 324	22, 602
Nicaragua		29	100	
Panama		4		25
Total	664, 964	572, 657	580, 940	445, 815
South America:				
Argentina	475	101		60
Bolivia		315	12	500
Brazil	776	633	3, 641	3, 447
Chile	143	362	320	1, 800
Colombia	135	901	2, 378	1, 845
Ecuador		2	22	104
Peru	10	172	222	602
Surinam				11
Uruguay			10	
Venezuela	8, 630	91	10	98
Total	10, 169	2, 577	6, 615	8, 467
Europe:				
Iceland				67
Spain	22			20
Sweden				15, 400
U.S.S.R	27, 400	132, 240	47, 275	
Total	27, 422	132, 240	47, 275	15, 487
Africa:				
Algeria			500	
Union of South Africa	23, 014			
Total	23, 014		500	
Asia:				
Arabia Peninsula States			1	
China	8, 501		1	
India			1, 989	4, 441
Netherlands Indies	4, 480			
Turkey	11, 200			
Total	24, 181		1, 991	4, 441
Oceania:				
Australia	17, 920	3, 908	615	
Total	17, 920	3, 908	615	
Grand total	767, 670	711, 382	637, 936	474, 210

PRICES, TRANSPORTATION, OTHER ECONOMIC FACTORS

The prices of imported strontium minerals have not increased significantly since World War II because of competition of Mexican with English celestite, the potential competition by strontium minerals from other countries (Sicily, Germany, and others), and the threat of establishing a producing industry in the United States. Currently there is keen competition between British and Mexican material, both in price and in quality. The rapid and extreme fluctuation in United States consumers' quantity requirements stimulates, encourages, and intensifies this competition.

Early in World War I celestite was quoted f.o.b. Bristol dock at about $3 a short ton. By 1933 it had risen to about $7, and delivered at Atlantic coast ports it was $10 a short ton. Trade journal quotations for strontium minerals are nominal, but tables 8 and 9 summarize the approximate price history for the past two decades.

TABLE 8.—*Prices of strontium minerals, 1935–57*

[Bureau of Mines Minerals Yearbook]

Year	Declared value of imports (per short ton)		Trade journal quotations (per short ton)	
	United Kingdom	Mexico	Celestite [2]	Strontianite [3]
1935	$8. 53	(1)	$35	$60
1936	7. 45	(1)	35	60
1937	7. 39	(1)	35	60
1938	9. 64	(1)	35	55–$120
1939	8. 12	(1)	37	55
1940	10. 41	(1)	37–45	55
1941	15. 39	$15. 59	45	55
1942	13. 76	10. 93	45	55
1943	15. 62	13. 40	45	55
1944	(4)	12. 05	45	55
1945	(5)	12. 72	45	55
1946	16. 61	12. 22	45	55
1947	17. 12	14. 56	45	55
1948	17. 12	13. 43	54	55
1949	17. 61	12. 69	54	55
1950	17. 78	12. 11	54	55
1951	23. 42	11. 67	54	55
1952	20. 69	13. 01	56. 70–66. 15	(6)
1953	21. 09	12. 39	56. 70–66. 15	(6)
1954	20. 50	13. 06	56. 70–66. 15	(6)
1955	24. 87	13. 22	56. 70–66. 15	(6)
1956	22. 71	12. 20	56. 70–66. 15	(6)
1957	23. 03	12. 08	56. 70–66. 15	(6)

[1] No production until 1941.

[2] 1935–40—finely powdered, carlots, 90 percent $SrSO_4$; 1940–51—finely powdered, carlots, 92 percent $SrSO_4$; 1952–57—air floated, 90 percent $SrSO_4$, 325-mesh, bags, works.

[3] Lump, carlots, minimum 84–86 percent $SrCO_3$, nominal.

[4] Imports less than 1 ton.

[5] No imports.

[6] Not quoted.

RAIL RATES

The 1957 railroad freight rate on crude celestite from (for example) Barstow, Calif., to Philadelphia, Pa., or Grasselli, N.J., minimum 60,000-pound cars, was $2.53 per 100 pounds ($50.60 per short ton). The authority for this quotation is Transcontinental Freight Bureau Tariff Rate 1015. Rates from Brownwood, Tex., to Philadelphia and Grasselli are $1.44 and $1.49 per 100 pounds, respectively. From Sweetwater, Tex., to those same points the rates are $1.48 and $1.53 by authority of Southwestern/Eastern Freight Tariff 1005. All these rates include the 7-percent increase effective December 28, 1956.

The rate on celestite concentrates from Barstow to Philadelphia and Grasselli is $2.875 per 100 pounds; from Brownwood to Philadelphia $6.29 and to Grasselli $6.61; from Sweetwater to Philadelphia $6.61 and to Grasselli $6.77. (NOTE: All the above rates can be checked by addressing an inquiry to either Federal

TABLE 9.—*Prices per pound of selected strontium compounds, 1930–57*

[Oil, Paint and Drug Reporter]

Year	Strontium carbonate		Strontium nitrate	Strontium chloride; tech.	Strontium iodide	Strontium oxalate
	Pure	Tech.				
1930	\$0.25–\$0.26	(1)	(1)	(1)	\$4.00–\$4.10	(1)
1931	(1)	\$0.07¼–\$0.07½	\$0.07 –\$0.09¼	(1)	(1)	(1)
1932	.26 – .36	(1)	(1)	(1)	3.00– 3.05	(1)
1933	.26 – .36	(1)	.07¼– .07½	(1)	2.95– 3.05	(1)
1934	.26 – .36	(1)	.07¼– .09½	(1)	2.85– 3.00	(1)
1935	.30 – .31	(1)	.08¾– .09¾	(1)	2.85– 2.90	(1)
1936	.30 – .31	(1)	.07¾– .09¾	(1)	2.80– 2.85	(1)
1937	.30 – .31	(1)	.07¾– .08¾	(1)	2.70– 2.85	(1)
1938	.30 – .32	(1)	.07¾– .08¾	(1)	2.70– 2.90	(1)
1939	.30 – .32	.16½– .24	.07¾– .08¾	\$0.11–\$0.19	2.85– 3.06	(1)
1940	.30 – .32	.22 – .25	.07¾– .08¾	.20– .22	3.00– 3.06	(1)
1941	(1)	.15 – .18	.07¾– .08¾	.22– .35	3.00– 3.06	\$0.44
1942	(1)	.15 – .18	.07¾– .08¾	.22– .25	3.00– 3.06	.44
1943	.23 – .25	.14 – .16	.07¾– .08¾	.23– .25	3.00– 3.06	.37½–\$0.44
1944	.23 – .25	.14 – .16	.07¾– .08¾	.22– .24	3.00– 3.15	.37½
1945	.23 – .25	.14 – .16	.07¾– .08¾	.22– .24	3.00– 3.15	.38 – .40
1946	.23 – .25	.14 – .16	.07¾– .08¾	.22– .24	3.00– 3.15	.38 – .40
1947	.23 – .25	.14 – .16	.07¾– .08¾	.22– .24	3.00– 3.06	.38 – .40
1948	.23 – .25	.14 – .16	.07¾– .08¾	.22– .24	3.00– 3.60	.38 – .40
1949	(1)	.15½– .16½	.09¼– .10¼	.22– .24	3.60	.42 – .44
1950	(1)	.15½– .16½	.09¼– .10¼	.22– .24	3.37– 3.60	.42 – .44
1951	(1)	.15½– .20½	.10¼– .11¼	.22– .24	3.37	.42 – .44
1952	.20½– .25	(1)	.10¼– .11	.22– .26	3.37	(1)
1953	.23 – .33	.19	.10¼– .12	.24– .26	3.37– 3.42	(1)
1954	.33 – .35	.19	.11 – .12	(1)	3.42	(1)
1955	.35	.19	.11 – .12	(1)	3.42	(1)
1956	.35	.19	.11 – .12	(1)	3.42	(1)
1957	.35 – .37	.19	.11 – .12	(1)	3.42– 3.57	(1)

(1) Price not quoted.

Supply Service, D.C. Regional Office, or to the ICC.)

OCEAN FREIGHT RATES

Transatlantic freight rates from Bristol, England, to Philadelphia (and other North Atlantic United States ports) increased from \$4.40 per short ton in 1939 to \$5.90 per ton in 1940. The increase was due to a 33⅓-percent war surcharge. The current trans-Atlantic rate is about \$10 to \$14 per ton.

TARIFF

Celestite and strontianite are and always have been on the list of materials that may be imported into the United States, free of duty.

United States import duties on strontium levied by tariff acts and trade agreements follow:

Tariff Act of 1922

TITLE I

Dutiable List

Schedule 1.—Chemicals, oils, and paints

Par. 87. Strontium: Carbonate, precipitated, nitrate, and oxide, 25 per centum ad valorem.

TITLE II

Free List

SECTION 201. That on and after the day following the passage of this Act, except as otherwise specially provided for in this Act, the articles mentioned in the following paragraphs, when imported into the United States or into any of its possessions (except the Philippine Islands, the Virgin Islands, and the islands of Guam and Tutuila), shall be exempt from duty:

Par. 1676. Strontianite or mineral strontium carbonate and celestite or mineral strontium sulphate.

Tariff Act of 1930 (Public Law No. 361)

TITLE I—DUTIABLE LIST

Schedule 1.—Chemicals, Oils, and Paints

Par. 85. Strontium: Carbonate, precipitated, nitrate, and oxide, 25 per centum ad valorem.

Schedule 3.—Metals and Manufactures of

Par. 302(n). Barium, boron, calcium, columbium or niobium, strontium, tantalum, thorium, titanium, uranium, vanadium, zirconium, alloys of two or more of these metals, or alloys not specially provided for of one or more of these metals with one or more of the metals aluminum, chromium, cobalt, copper, manganese, nickel, or silicon, 25 per centum ad valorem.

TITLE II—FREE LIST

SECTION 201. That on and after the day following the passage of this Act, except as otherwise specially provided for in this Act, the articles mentioned in the following paragraphs, when imported into the United States or into any of its possessions (except the Philippine Islands, the Virgin Islands, American Samoa, and the island of Guam), shall be exempt from duty:

Schedule 16

Par. 1776. Strontianite or mineral strontium carbonate and celestite or mineral strontium sulphate.

Tariff Agreements—

The tariffs as established under the Tariff Act of 1930 were reduced by concessions granted at the Torquay sessions of the General Agreement on Tariffs and Trade.

Present tariffs on strontium compounds (par. 85, Tariff Act of 1930) were reduced to 12½ percent ad valorem.

Additional reductions on the items listed in paragraph 302(n) of the Tariff Act of 1930 are as follows(*45*):

	Full rate (Percent)	*Reduced rate (Percent)*
Barium, boron, columbium, or niobium, strontium, tantalum, thorium, vanadium, and zirconium.	25 ad val.	12½ ad val.
Calcium	25 ad val.	17½ ad val.
Titanium	25 ad val.	20 ad val.
Uranium	25 ad val.	
Alloys of 2 or more of the above-named metals:		
Containing uranium but not containing columbium or niobium, or tantalum.	25 ad val.	
Other	25 ad val.	12½ ad val.
Alloys of 1 or more of the above-named metals with 1 or more of the metals aluminum, chromium, cobalt, copper, manganese, nickel, or silicon:		
Calcium silicon and zirconium silicon.	25 ad val.	12½ ad val.
Containing uranium	25 ad val.	
Other	25 ad val.	20 ad val.

TABLE 10.—*World production of strontium minerals, by countries, 1925–56*

(In short tons)

Year	Argentina	Australia	Canada	France	Germany	Italy	Mexico[1]	Pakistan	Spain	Tunisia	United Kingdom	United States	Total
1925				3, 248	896						2, 996		7, 140
1926				1, 680	(2)						2, 381		4, 061
1927				1, 008	795						4, 538		6, 341
1928				1, 120	959						7, 981		10, 060
1929				896	803						5, 969		7, 668
1930				840	402					560	5, 758		7, 560
1931				112	143					560	4, 538		5, 353
1932				246	73					22	7, 674		8, 015
1933				672	168						4, 325		5, 165
1934				224	381						10, 573		11, 178
1935					204						5, 051		5, 255
1936					289						6, 396		6, 685
1937					300						8, 509		8, 809
1938					(2)						5, 148		5, 148
1939										143	4, 212		4, 355
1940										209	4, 140	350	4, 699
1941	4	80	27				987			101	(2)	4, 750	5, 949
1942		36					6, 201		5, 238	22	2, 517	4, 041	18. 055
1943							11, 060		11, 797			7, 566	30, 423
1944							3, 170		11, 107			3, 005	17, 282
1945							3, 016			66		2, 784	5, 866
1946							1, 977			125		243	2, 345
1947							3, 937			256	5, 613		9, 806
1948				309			1, 114			132	8, 296		9. 851
1949			[1] 59				1, 158				5, 369		6, 586
1950							1, 975	(2)		166	7, 451		9, 592
1951			[1] 38				2, 034	152		474	18, 312		21, 010
1952			[1] 50			28	1, 297	482		34	9, 072		10, 972
1953			[1] 43				2, 441	918			3, 321	50	6, 773
1954							1, 906	391			2, 352	12	4, 661
1955						77	2, 072	486			5, 320	177	8. 132
1956	401					234	2. 313	246			10, 304	4, 022	17, 520
Total	405	116	226	10, 355	5, 413	339	46, 658	2, 675	28, 142	2, 870	168, 116	27, 000	292, 315

[1] Based on United States imports.
[2] Not available.

CHAPTER 5. WORLD PRODUCTION AND INTERNATIONAL TRADE

WORLD PRODUCTION

MINERALS

The leading producers of strontium minerals are the United Kingdom, Mexico, and Germany. Other countries that have produced strontium minerals include Canada, France, Pakistan, Tunisia, Argentina, Australia, Italy, and Spain. (Figures on world production for 1925–56 can be found in table 10.)

The first commercial production of strontium minerals was in Germany, with the opening of the Westphalian strontianite deposits in 1840 (*20*). By 1875 production had risen to 220 tons; and by 1884, because of the newly developed use for strontium hydroxide in recovering sugar from beet-sugar molasses, production had skyrocketed to 8,850 tons. (See table 11.) It was during this period that the British celestite deposits, which were opened in 1875, increased production to the point where they dominated the world market, and German production began to decline. After the First World War production in Germany averaged little more than 350 tons per year.

TABLE 11.—*Production of strontianite in Germany during specified years, 1840–1925 (20)*

Year	Short tons	Year	Short tons
1840	34	1919	46
1875	220	1920	77
1883	8, 340	1921	683
1884	8, 850	1922	330
1915	28	1923	NA
1916	176	1924	683
1917	358	1925	896
1918	304		

The celestite deposits in England were discovered about 1799; however, it was not until 1875 that the first commercial production was recorded. By 1884 British celestite had established the dominant position on the world strontium market that it still holds. (See table 12.) Before World War I most of the British celestite was sent to Germany for use in the sugar-refining industry or to be manufactured into strontium compounds for export; and, except for the period 1914–18, England's requirements for strontium chemicals were satisfied by imports from Germany.

TABLE 12.—*Celestite production in the United Kingdom, 1884–1925* [1]

Year	Short tons	Year	Short tons	Year	Short tons
1884	12, 793	1898	14, 494	1912	21, 694
1885	10, 976	1899	14, 144	1913	20, 636
1886	15, 234	1900	10, 216	1914	14, 736
1887	16, 989	1901	18, 649	1915	717
1888	7, 912	1902	36, 155	1916	2, 815
1889	6, 693	1903	25, 583	1917	2, 886
1890	11, 509	1904	20, 349	1918	1, 136
1891	9, 028	1905	16, 009	1919	2, 097
1892	5, 674	1906	15, 805	1920	4, 685
1893	6, 509	1907	12, 034	1921	7, 417
1894	7, 642	1908	18, 445	1922	5, 276
1895	13, 746	1909	15, 727	1923	8, 761
1896	20, 207	1910	5, 332	1924	3, 367
1897	16, 785	1911	6, 573	1925	2, 996

[1] Data for 1884–1914 from Sherlock, R. L., Celestine and Strontianite, in Special Reports on the Mineral Resources of Great Britain, vol. III, 1915, p. 52; data for later years from publication *12* of Bibliography.

In 1956 three firms supplied the total output of celestite in England; they were:

Bristol Mineral and Land Company, Ltd.
Strontium Products, Ltd.
British Quarrying Company, Ltd.

During the past 15 years, Mexico has also become an important world supplier of strontium minerals. In 1941 celestite production was begun from a mine in the Matehuala district, San Luis Potosi. Since that time mining has also been started in the State of Coahuila, and more than 40,000 tons of celestite has been produced.

Since 1955 strontium mineral production in Italy has increased. In 1957 production totaled 1,226 short tons—an increase of almost 1,000 tons over 1956.

The cost of Italian strontium-mineral output is high. When prices are low, the Italian product has difficulty competing with British, German, and Mexican material. However, when there is an increase in price, Italy can compete on the world market.

Production of strontium minerals in Canada, France, Pakistan, Tunisia, Argentina, Australia, and Spain is small; it is used chiefly to satisfy demands of local chemical firms and occasionally provide small quantities for export.

CHEMICALS

From the middle of the 19th century until the 1930's Germany was the world's leading supplier of strontium chemicals. Since that time, Germany's position in the field has been equaled and surpassed by the strontium-chemical industries of the United Kingdom and the United States. France and Italy are also important contributors to the world's strontium-chemical supply.

The manufacture of strontium chemicals in England did not begin until 1937, when Albright and Wilson, Ltd., Birmingham, entered into the commercial production of strontium compounds. The industry has expanded, and at present, three firms in England are manufacturing strontium salts. At least six firms in Germany and eight firms in Italy are also producing strontium compounds.

Some of the firms in European countries that are known to manufacture strontium salts follow:

England

Cornwall Mills, Ltd., The Harbor Par., Cornwall.
La Porte Chemicals, Ltd., Leeton.
New Metals and Chemicals, Ltd., 16 Northumberland Ave., London.

Germany

Lohman Chemische Fabrik, Hameln.
Marquart A. G. Chemische Fabrik, Beuel Rhein.
Merck, E. A. G., Darmstadt.
Rickmann & Rappe, Koln-Kalk.
Rickmann de Haen A. G., Seelze (Hann.).
Siegle G. & Co., G.m.b.H., Stuttgart—Feuerback.

Italy

Erba Carlo, Sp. A., Milano.
Fabbr. Sali di Bario Concimi ed altri Prod. Chim., S. A., Milano.
Industria Chimica Subalpina, Genova.
Montecatini Soc. Gen. per l'Industria, Mineraria e Chimica, Milano.
Sinfar—S.r.l. Novi Ligure (Alessandria).
Soc. Italiana del Bromo, Roma.
Squeo dr. Marcello—Industria Chimica, Milano.
Zambeletti dr. L. Soc. p. Az., Milano.

POLITICAL AND COMMERCIAL CONTROL

The deposits of celestite in England are controlled and mined by small, independent firms composed of British nationals. Individual farmers in the area occasionally add to the supply.

Although United States firms give financial aid and purchase contracts to one or more producers in Mexico, all the production is currently controlled by Mexican nationals. Most of the imports are made through a United States minerals brokerage firm.

INTERNATIONAL TRADE

Great Britain normally supplies almost all of the world's requirements for celestite. Because of the low cost of mining and accessibility to cheap water transportation, it is difficult for other nations to compete. The British Ministry of Mines reported that in 1947, 80 percent of the United Kingdom production of celestite was exported to the United States. It was reported further that in 1951 the United Kingdom exported 95 percent of its production; of this output, 90 percent was destined for the "dollar" countries (*38*). In addition to exporting celestite, Great Britain also exports some strontium chemicals. Table 13 presents world exports of strontium minerals and compounds.

Germany produces and exports small quantities of strontianite and also finished strontium compounds. Before the Second World War most German exports of strontium chemicals and strontianite went to the United States. In 1938, 73 short tons of strontium chemicals was exported from Germany, 41 tons of which reached the United States. Exports of strontianite and witherite amounted to 400 short tons during that year.

Mexican celestite is exported, for the most part, to the United States, with occasional small shipments to markets in other countries.

Spanish celestite was shipped to the United States from 1942–45 and 1947–49, primarily to meet increased demands of the strontium-chemical industry during the war years and also for inclusion in the national stockpile. However, since 1949 the United States has not imported any material from this country. Spain also provided celestite for the German strontium chemical market in the early years of the Second World War.

Italy is also an exporter of strontium minerals and chemicals, but the volume of exports is much smaller than those of the United Kingdom, Mexico, and Germany. Table 14 shows the exports of strontium minerals and compounds from Italy.

The quantity of strontium minerals and compounds involved in world trade is small compared with many other mineral commodities. Because of this fact, many nations do not give strontium chemicals a separate classification on import-export schedules and usually class them with other nitrates, carbonates, oxides, etc. This results in lack of statistical data on foreign trade and presents some difficulties in establishing trade patterns.

It is believed that almost every nation in the world imports or has imported strontium minerals and compounds. Most Latin American countries import small quantities annually for use by local chemical and pyrotechnic industries.

Table 15 contains some data on the imports of three South American countries.

TABLE 13.—*World exports of strontium minerals and compounds,*[1] *1940–56*

(In short tons)

Exporting country	1940	1941	1942	1943	1944	1945	1946	1947	1948
North America:									
Canada: Sr minerals	--------	--------	--------	--------	--------	--------	--------	--------	--------
Mexico: Celestite [2]	--------	987	6, 201	11, 060	3, 170	3, 016	1, 977	3, 937	1, 114
United States: Sr cmpds	(3)	(3)	384	356	319	237	(3)	(3)	(3)
Europe:									
France:									
Sr cmpds	164	84	22	22	16	3	15	10	(3)
Strontianite	--------	--------	--------	--------	--------	--------	--------	--------	--------
Germany:									
Sr cmpds	4	11	17	115	[4] 3	(3)	(3)	(3)	--------
Strontianite and witherite [5]	67	34	164	86	[4] 69	(3)	(3)	(3)	17
Italy: Strontianite and celestite	--------	--------	--------	--------	--------	--------	--------	--------	--------
Spain: Celestite [2]	--------	--------	1, 475	4, 454	2, 622	695	--------	5, 836	14, 614
United Kingdom: Celestite [2]	2, 429	3, 306	2, 682	1, 367	--------	--------	2, 530	4, 344	6, 043
Africa: Tunisia: Sr minerals	22	(3)	(3)	(3)	(3)	(3)	(3)	(3)	115

Exporting country	1949	1950	1951	1952	1953	1954	1955	1956
North America:								
Canada: Sr minerals	[2] 59	--------	[2] 38	[2] 59	[2] 43	--------	--------	--------
Mexico: Celestite [2]	1, 158	1, 975	2, 034	1, 297	2, 441	1, 906	2, 072	2, 313
United States: Sr cmpds	(3)	(3)	(3)	(3)	(3)	(3)	(3)	(3)
Europe:								
France:								
Sr cmpds	(3)	--------	18	7	1	--------	(3)	(3)
Strontianite	12	3	11	--------	--------	2	6	(3)
Germany:								
Sr cmpds	--------	12	17	--------	--------	--------	(3)	--------
Strontianite and witherite [5]	22	20	[6] 55	--------	--------	--------	[7] 13	30
Italy: Strontianite and celestite	--------	[8] 178	1, 077	1	47	--------	--------	7
Spain: Celestite [2]	3, 263	--------	--------	--------	--------	--------	--------	--------
United Kingdom: Celestite [2]	4, 904	6, 655	11, 972	8, 161	4, 413	1, 385	4, 053	7, 119
Africa: Tunisia: Sr minerals	166	(3)	553	(3)	--------	--------	772	(3)

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[1] Figures for France, Germany, Italy, United Kingdom, and Tunisia compiled from Colonial Geological Surveys, Mineral Resources Division, Statistical Summary of the Mineral Industry (production, imports and exports), H. M. Stationery Office, London, England; annual publication.

[2] Figures based on United States imports.

[3] Not available.

[4] January–July only.

[5] Strontianite and witherite not separately classified on import-export schedules; celestite exports included with barite.

[6] January–September only.

[7] New classification—strontianite and celestite.

[8] July–December only.

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TABLE 14.—*Exports of strontium minerals and compounds from Italy,*[1] *1950–56*

(In pounds)

Article and country of destination	1950	1951	1952	1953	1954	1955	1956
Strontianite and celestite:							
Australia	-----	-----	-----	126	-----	-----	-----
Austria	-----	2, 156, 033	-----	-----	-----	-----	-----
Belgium and Luxembourg	-----	-----	2, 183	-----	-----	-----	-----
British Malaya	-----	-----	207	-----	-----	-----	-----
Egypt	-----	-----	-----	88, 669	-----	-----	-----
Netherlands	55	-----	-----	-----	-----	-----	-----
Union of South Africa	-----	-----	168	-----	-----	-----	-----
United States	-----	-----	-----	-----	-----	-----	13, 227
West Germany	357, 277	-----	265	4, 409	-----	-----	-----
Total	357, 332	2, 156, 033	2, 823	93, 204	-----	-----	13, 227
Strontium hydroxide and oxide:							
Hungary	-----	-----	-----	66, 138	-----	-----	-----
Switzerland	-----	-----	-----	-----	-----	440	-----
Turkey	-----	-----	22, 000	-----	-----	-----	-----
United States	-----	315	-----	-----	-----	-----	-----
Strontium carbonate:							
Bulgaria	-----	-----	-----	-----	-----	2, 205	-----
Poland	-----	-----	-----	8, 818	5, 732	-----	-----
Switzerland	-----	-----	-----	-----	-----	-----	595
United Kingdom	-----	-----	9, 259	-----	-----	-----	-----
United States	-----	-----	-----	1, 213	6, 614	-----	820
Total	-----	315	31, 259	76, 169	12, 346	2, 645	1, 415

[1] From Annual Statistics of Foreign Commerce, Central Institute of Statistics, Republic of Italy, Rome.

TABLE 15.—*Imports of strontium compounds into Brazil, Chile, and Colombia, 1952–56, in pounds*[1]

Importing country	Origin of imports	1952	1953	1954	1955	1956
Brazil	France	-----	-----	2, 205	-----	-----
	Germany	-----	-----	110	-----	4, 982
	United States	-----	866	7, 732	97	1, 100
Total	-----	-----	866	10, 047	97	6, 082
Chile	Germany	108	105	334	(2)	(2)
	Great Britain	882	-----	-----	(2)	(2)
	United States	-----	124	723	(2)	(2)
Total	-----	990	229	1, 057	(2)	(2)
Colombia	Germany	-----	-----	2, 103	(2)	2
	United States	752	617	223	(2)	-----
Total	-----	752	617	2, 326	(2)	2

[1] Data from the annual foreign commerce bulletins of Brazil, Chile, and Colombia.
[2] Not available.

Turkey is also a regular importer of strontium compounds. (See table 16.)

TABLE 16.—*Turkish imports of strontium compounds, 1942–55*

Year	Pounds	Year	Pounds
1942	11, 200	1949	2, 240
1943	-----	1950	1, 025
1944	2, 240	1951	2, 240
1945	2, 240	1952	2, 240
1946	-----	1953	2, 240
1947	2, 240	1954	2, 240
1948	22, 400	1955	4, 480

Peru, Venezuela, Mexico, Cuba, France, Italy, and many other nations import strontium minerals and compounds.

CHAPTER 6. STRONTIUM INDUSTRY IN WORLD WAR II AND KOREAN EMERGENCY

From World War I until the beginning of World War II there was virtually no domestic strontium-mining industry except the small output of impure celestite mined and ground in Texas for use in well-drilling mud. During that period nearly all United States requirements for strontium minerals were imported from Great Britain, supplemented by imports of strontium chemicals from Germany. The wartime blockade late in 1939 developed some uncertainties in the supply of these chemicals.

The beginning of World War II saw an immediate and pronounced increase in the military requirements for strontium compounds for tracer bullets and ammunition, fusées, flares, rockets, and other safety, distress, warning, and visual signaling devices. Soon after the outbreak of hostilities in 1939 imports of strontium chemicals from Germany were cut off. In December 1940 strontium metal and salts were added to the list of commodities that could not be exported except under license. However, anticipated shortages of celestite did not actually develop. Imports were maintained. Supplies came largely from Great Britain in 1940, but a deposit of high-grade celestite in Mexico was developed in 1940, and exports of the material to the United States began in January 1941.

Anticipating large demands for strontium salts, potential domestic producers hastened to reopen mines that had been idle since World War I. Several resumed production on a small scale. Domestic production in 1940, as reported by six producers in California, Ohio, Texas, and Washington, was less than 350 tons (excluding a considerable tonnage of ground celestite for use in oil-well drilling fluids).

Wartime military requirements for strontium salts for tracer bullets and signal flares, superimposed upon increased civilian requirements, created a small market in 1941 for celestite producers on the west coast, where the mines had been virtually idle since 1918. Shipments of strontium minerals in 1941 totaled 4,724 short tons compared with less than that quantity in 1940. Import data indicated increased receipts of celestite from England and substantial quantities from Mexico.

Sales of celestite by domestic producers declined slightly in 1942. No new deposits of Chemical grade were worked commercially. Production of Subchemical-grade celestite in Texas for well drilling declined with curtailment in drilling activity, although some of the high-grade rock was sold for purifying caustic soda and conversion to strontium chemicals both with and without beneficiation. Research by the Bureau of Mines and the Foote Mineral Co. on beneficiating crude celestite from Brown and Nolan Counties, Tex., indicated that the impure celestite could be beneficiated to a plus-92-percent strontium sulfate. Imports of celestite into the United States in 1942 amounted to 10,358 short tons, mostly from Mexico, compared with 4,293 tons in 1941, mostly from the United Kingdom.

Shipments of celestite by United States producers in 1943 totaled 7,566 tons, compared with 4,041 tons in 1942 (figures include chemical and nonchemical). Consumption of celestite in manufacturing chemicals in 1943 was 13,732 tons, held mostly by the Metals Reserve Company. Imports were 16,881 tons principally from Mexico.

The Office of Price Administration on February 16, 1943, issued Maximum Price Regulation MPR 327 which had to do with celestite, among other substances. Sections of this regulation were as follows:

OFFICE OF PRICE ADMINISTRATION MAXIMUM PRICE REGULATION 327—CERTAIN NONMETALLIC MINERALS

1438.1 Commodities Subject to this Maximum Price Regulation 327. The provisions of this Maximum Price Regulation No. 327 apply to the nonmetallic minerals set forth in the following list whether in ore, concentrate, ground, meshed, expanded, or other form, quality or state. For the purposes of this Maximum Price Regulation No. 327 each form, quality or state of any such minerals shall be considered a distinct commodity.

Agate
Andalusite
Aplite
Asbestos
Barite
Bentonite
Celestite
Corundum
Cryolite
Diatomaceous Earth
Dumortierite
Emery
Feldspar
Flint
Fuller's Earth
Garnet
Gilsonite
Graphite
Greensand
Iceland Spar
Ilmenite
Industrial Diamonds
Kaolin
Kieselguhr
Kyanite
Nepheline Syenite
Olivine
Pumice
Pumicite
Quartz Pebbles
Roofing Granules
Rutile
Sepiolite
Sillimanite
Strontianite
Topaz
Tripoli
Vermiculite
Witherite

1438.2 Maximum Prices for Commodities Listed in 1438.1—(a) Maximum Prices, Except as Provided in Paragraph (b) of this 1438.2. On and after February 22, 1943, regardless of any contract, agreement, lease or other obligation, no person shall sell or deliver, and no person shall buy or receive in the course of trade or business from any seller, any of the commodities listed in 1438.1, at a price in excess of the following maximum prices, and no person shall agree, offer, solicit, or attempt to do so.

(1) The seller's maximum price shall be the highest net price charged by him for the same commodity on a delivery made during March 1942 to a purchaser of the same class.

(2) If no such delivery was made by the seller during March 1942, the seller's maximum price shall be his highest net offering price for the same commodity in March 1942, to a purchaser of the same class.

(3) Whenever any seller is unable to determine his maximum price under paragraph (a)(1) and (a)(2) of this section for any commodity covered by this regulation (each form, quality or state of each mineral being considered a distinct commodity), his maximum price shall be determined as follows:

(i) If his maximum price was determined prior to February 22, 1943, in accordance with the provisions of the General Maximum Price Regulation, that price shall be the seller's maximum price for that commodity.

(ii) In all other cases the seller shall determine the net price at which he expects to sell his commodity and shall then file such net price with the Office of Price Administration for approval as his maximum price. Such proposed selling price shall be filed with the Office of Price Administration, Second and D Sts., S.W., Washington, D.C., within fifteen days after the first sale of the commodity that is made on or after February 22, 1943.

Pending action by the Price Administrator of prices submitted for approval under this paragraph (a)(3)(ii), any such seller may sell, deliver, exchange, or offer to sell, deliver or exchange, and any person may buy, offer to buy or receive from such seller any such commodity at the price submitted for approval. If, however, the Price Administrator disapproves the price submitted, the selling price shall be revised downward to the maximum price which the Price Administrator shall approve, and any payment made in excess of the price so approved may be required to be refunded to the buyer within fifteen days after the date of the order informing the seller of such revision. In the absence of notice to the contrary from the Office of Price Administration within thirty days after a seller files such a selling price with the Office of Price Administration, the price filed shall stand approved and shall be the maximum price applicable.

When filing such a price with the Office of Price Administration, the seller shall set forth, in addition to the net price, his list price, and all discounts, allowances, and differentials for all classes of buyers, a description and identification of the commodity, a statement of facts differentiating such commodity from the other commodities sold by the seller, a statement showing how the proposed price was determined, and a description of the use or uses for which the commodity is to be produced.

Section 1438.2(b) provided maximum prices for certain commodities sold by a list of firms among which was the Pan Chemical Company. Section 5, under this paragraph, provided as follows: "The Pan-Chemical Company, 205 First National Bank Building, Pomona, California may sell and deliver, and any person may buy and receive from the Pan-Chemical Company celestite having a minimum content of 90% strontium sulphate and a maximum content of 4½% calcium sulphate at a price not in excess of $18.67 per short ton, f.o.b. Westmorland, California."

1438.14 Effective Date. This Maximum Price Regulation No. 327 (par. 1438.1 to 1438.14, inclusive) shall become effective February 22, 1943 for the District of Columbia and the forty-eight states of the United States and shall become effective April 12, 1943 for the territories and possessions of the United States."

Issued this 16th day of February 1943.

Prentiss M. Brown,
Administrator.

Subsequent amendments to this MPR did not alter the prices for celestite.

Requirements for strontium compounds in signal flares and tracer bullets declined sharply in 1944, and activity in the domestic industry was maintained chiefly by a demand for well-drilling weight material that could not be supplied by barite producers. Small quantities of domestic celestite were sold for adsorbing iron from caustic soda and for chemicals. Shipments of celestite by producers totaled 3,005 short tons in 1944. Imports for consumption were 5,792 tons. Mexico was again the principal supplier. Consumption of celestite in making strontium chemicals totaled about 6,000 tons.

The celestite industry waned further in 1945, only four producers reporting shipments of 2,784 tons. As war demands eased, barite became more plentiful for use in drilling muds; requirements for strontium chemicals in tracer bullets and flares were also reduced drastically. Celestite producers were forced to seek additional outlets, generally local, such as in purifying caustic soda solutions and making small quantities of strontium chemicals for peacetime application.

In 1946 the domestic celestite-mining industry almost disappeared. Founded in the late 1930's as a substitute for barite in drilling fluids, the industry received impetus during the war years as a source of raw material for military requirements. In 1946 those markets were gone. The patent on the use of barite in drilling muds expired in 1943 and with it the $17 per ton royalty that had permitted celestite to compete. Two producers in California sold small quantities.

Only one producer in California continued activity in 1947, producing small quantities of celestite and strontianite and shipping only sample lots, which were not of commercial grade. Imports from Spain which had been received during the war years and discontinued in 1946 were resumed on an increased scale. This material represented the delivery of celestite purchased during the war on a preclusive buying program and was added to the national stockpile. Shipments of this material were completed in 1949.

No domestic production of strontium minerals was reported during 1948; however, imports for consumption were at a record rate for a peacetime year, representing largely increased deliveries from Spain under the preclusive buying agreement.

No domestic production of strontium minerals was reported during 1949, 1950, or 1951, except for sample lots.

To prevent hoarding and profiteering in mineral raw materials, the Defense Minerals Administration issued Mineral Order 1, Designation of Scarce Materials, on December 29, 1950, which made it unlawful to accumulate any raw mineral materials listed in the notice in excess of reasonable demands of business, home, or personal consumption, as for resale at a price higher than prevailing market prices. The mineral commodities on the list included strontium ores.

STOCKPILING

Although not under active procurement, in 1958 celestite is considered a strategic material and is on the Current List of Strategic and Critical Materials For Stockpiling. The list of these materials issued by the Office of Defense Mobilization is as follows:

EXECUTIVE OFFICE OF THE PRESIDENT
OFFICE OF DEFENSE MOBILIZATION

September 12, 1957

SUBJECT: CURRENT LIST OF STRATEGIC AND CRITICAL MATERIALS FOR STOCKPILING

Sec. 1. Purpose. The materials listed herein are currently included in the strategic stockpiling program pursuant to Section 2(a) of Public Law 520, 79th Congress.

Sec. 2. Group I Materials. The following list constitutes Group I of the materials in the strategic stockpile. These materials have been or may be acquired through purchase pursuant to Section 3(a), and by transfer of Government-owned surpluses pursuant to Section 6(a), of Public Law 520, 79th Congress. All materials purchased must conform to stockpile specifications. Some of these materials are not under active procurement.

1. Abrasives, Crude Aluminum Oxide
2. Agar
3. Aluminum
4. Antimony
5. Asbestos, Amosite
6. Asbestos, Chrysotile
7. Asbestos, Crocidolite
8. Bauxite, Metal Grade
9. Bauxite, Refractory Grade
10. Beryl
11. Bismuth
12. Cadmium
13. Castor Oil
14. Celestite
15. Chromite, Chemical Grade
16. Chromite, Metallurgical Grade
17. Chromite, Refractory Grade
18. Cobalt
19. Coconut Oil
20. Columbite
21. Copper
22. Cordage Fibers, Abaca
23. Cordage, Fibers, Sisal
24. Diamond Dies, Small
25. Diamonds, Industrial—Bort & Stones
26. Feathers and Down, Waterfowl
27. Fluorspar, Acid Grade
28. Fluorspar, Metallurgical Grade
29. Graphite, Ceylon—Crystalline and Amorphous
30. Graphite, Madagascar—Crystalline Flake and Fines
31. Graphite, Other Than Ceylon and Madagascar—Crystalline
32. Hyoscine
33. Iodine
34. Jewel Bearings
35. Lead
36. Magnesium
37. Manganese, Battery Grade, Natural Ore
38. Manganese, Battery Grade, Synthetic Dioxide
39. Manganese, Chemical Grade, Type A Ore
40. Manganese, Chemical Grade, Type B Ore
41. Manganese Ore, Metallurgical Grade
42. Mercury
43. Mica, Muscovite Block, Stained A/B and Better
44. Mica, Muscovite Film, First and Second Qualities
45. Mica, Muscovite Splittings
46. Mica, Phlogopite Splittings
47. Molybdenum
48. Nickel
49. Opium
50. Palm Oil
51. Platinum Group Metals, Iridium
52. Platinum Group Metals, Palladium
53. Platinum Group Metals, Platinum
54. Pyrethrum
55. Quartz Crystals
56. Quinidine
57. Rare Earths
58. Rubber, Crude Natural
59. Selenium
60. Shellac
61. Silicon Carbide, Crude
62. Silk, Raw
63. Silk Waste and Noils
64. Sperm Oil
65. Talc, Steatite, Block
66. Tantalite
67. Tin
68. Tungsten
69. Vanadium
70. Vegetable Tannin Extract, Chestnut
71. Vegetable Tannin Extract, Quebracho
72. Vegetable Tannin Extract, Wattle
73. Zinc

Sec. 3. Group II Materials. The following list constitutes Group II of the materials in the strategic stockpile. These materials have been acquired principally through transfer of Government-owned surpluses pursuant to Section 6(a) of Public Law 520, 79th Congress. None is under procurement.

1. Bauxite, Abrasive
2. Corundum
3. Cryolite, Natural
4. Diamond Dies, Other Than Small
5. Mica, Muscovite Block, Stained B and Lower
6. Mica, Phlogopite Block
7. Rutile
8. Sapphire and Ruby
9. Talc, Steatite, Ground
10. Titanium Sponge
11. Wool

Sec. 4. Effective Date. This list supersedes all previous lists and is effective immediately.

Geo. B. Beitzel,
Assistant Director for Production.

CHAPTER 7. STRONTIUM ISOTOPES

GENERAL

There are four stable *isotopes* and several unstable or radioactive isotopes of strontium. The stable isotopes have the following relative natural abundance: Sr^{84}—0.56 percent, Sr^{86}—9.86 percent, Sr^{87}—7.02 percent, and Sr^{88}—82.56 percent. The unstable isotopes of strontium are Sr$^{85, 89, 90, 91, 92, 93, 94, 95, 96, 97}$. Most of these active unstable isotopes have a relatively short half-life of a few to about 65 days (and in some instances minutes). However, Sr^{90} has a half-life of about 25 years, and herein lies one of the vexatious problems relating to the element strontium. Strontium 90 has no connection with natural deposits of celestite, strontianite, or other strontium-bearing minerals; it is a part of the radioactive debris that results from the explosion of some nuclear devices or weapons and is part of the fallout from such explosions. Strontium 90 also is a byproduct of waste of the fission of nuclear reactor fuels.

The chemical and physical characteristics of Sr^{90} that make it of particular importance among the fission products are: Its chemical similarity to calcium, which is essential to both plants and animals; a half-life of 25 years; concentration in bone and bone marrow and a low rate of elimination from bones; and its high-energy beta-ray emission.

The Sr^{90} dispersed into the stratosphere by megaton-range explosions has received specific attention from investigators, as this material literally covers the face of the globe, and the rate at which it falls to earth is beyond control. Some investigators have stated that measurements and calculations indicate that the fallout will result in a concentration on the earth's surface well below the maximum permissible limit. In addition, there appears to be a natural built-in safety factor or mechanism for protection against Sr^{90}. For example, milk usually contains only one-sixth the Sr^{90} content of the food eaten by the cow. Strontium 90 deposited on soil does not find its way into water supplies by leaching process, and the Sr^{90} content of rivers and lakes corresponds to only a little more than that accountable by direct fallout on the surface of the water.

Worldwide measurement of radioactivity is a continuing aspect of the program of the Atomic Energy Commission. Soils, waters, foodstuffs, and human and animal bones are sampled to ascertain the uptake and distribution of radioactive fission products, including strontium 90. Biological studies on the hazards of Sr^{90} are also being conducted (*53*).

Strontium 90 is being produced in increasingly larger quantities as a residual product of the atomic energy program. As fuel elements in reactors become spent (that is, no longer emit enough neutrons to sustain a chain reaction) they are removed from the reactor. A part of this residual material is Sr^{90}, a dangerously radioactive waste product.

Thus, storage or disposal of this material is a major problem and may become greater as the energy aspect of the program expands.

AVAILABILITY

The two radioactive isotopes of strontium, Sr^{89} and Sr^{90}, are produced and distributed by Oak Ridge National Laboratory. This laboratory also produces stable isotopes Sr$^{84, 86, 87, 88}$ in the production mass spectrograph. Because of limited supply of these electromagnetically separated isotopes they are available only on a loan basis.

APPLICATIONS

All the current applications of Sr^{90} and Sr^{89} utilize their beta-ray emission properties. Although the high-energy emission of these isotopes and the long half-life of Sr^{90} make them potentially more dangerous than many other available beta emitter isotopes, these very properties make them valuable and useful in several ways in industrial operations, the therapeutic and healing arts, and pure and applied research.

In industrial processes the most important use of Sr^{90} at present is in gages for continuous measurement of the thickness of sheet coating materials. These gages are either transmission or backscatter types. In the first type the beta rays are transmitted from the source through the material to be measured and then to a detector, usually an ionization chamber which in turn operates an electrometer. The measurement is of the mass per unit area of the material. Various types of dials or colored lights indicate the actual thickness of such sheet materials as plastics, textiles, rubber, linoleum, hardboards, glass, paper, tobacco, and foils of aluminum, copper, tin, brass, and steel being rolled at high speed. It helps producers maintain product uniformity, reduce the amount of rejected material, save on raw material, reduce number of inspection personnel, and increase operating speeds.

Beta-particle backscatter gages are used to measure the thickness of such coatings as metal plating, paint or ceramic on a base, plastic, or wires. A beta particle source is arranged near a detector (often in an annular ring around it) so that particles from the source cannot directly enter the detector, but so that both source and detector are exposed to the surface to be measured. The proportion of beta particles scattered back into the detector is measured (*50*).

Many major hospitals and clinics have a supply of Sr^{90} isotopes for use principally in radiotherapy of ophthalmic tumors, cutaneous lesions, and other types of ailments. In such applications a small particle of Sr^{90} is placed usually in the end of a small wand for topical shallow penetration of the affected area.

At present, however, probably the largest use for Sr^{90} is in pure and applied research. This convenient and available research tool is being used increasingly in research in such fields as medicine, agriculture, metallurgy, and plant and animal nutrition. For example, Sr^{90} has been used in studies of the effects of alterations in the blood supply of bones. Beta rays emitted by this isotope were used in these studies to determine very slight differences in bone densities. Nuclear theory shows that the percentage of their transmission by any material is proportional to the logarithm of the density of the material (*39*). Radioactive strontium has been tested as a treatment for bone cancer.

The increasing availability of Sr^{90} and the development of more efficient techniques of using this tracer have resulted in much additional work on the need for and effects of strontium. A number of tests have been conducted in this field, but factual data are still too sparse to permit definite conclusions as to relation of strontium to plant and animal nutrition. However, a number of researchers have expressed the opinion that strontium will be found essential to certain plants and animals, including humans.

Strontium 90 is now used commercially as the activator of the phosphors in self-luminous compounds as a substitute for radium. Radioisotope-activated light sources are considered to be superior to the radium-activated material because of the relatively low and predictable rate of decrease in luminous intensity, increased maximum brightness, and almost complete absence of external radiation. Strontium 90, because of its long half-life and very high maximum surface brightness it imparts to the light source, is used where the relatively thick shielding that is necessary for complete absorption of radiation and the increased weight are not problems.

Strontium 90 is used in a device to measure the density of salt at the bottom of lakes and streams.

Research is being conducted on the application of strontium 90 as the exciter for X-ray sources (Bremsstrahlung radiation).

The only process by which nuclear energy is converted directly into electrical power (the nuclear power reactor utilizes the heat of fission by harnessing it to a conventional steam engine or generator) is in the nuclear battery. The source of energy in these batteries is one of the radioactive isotopes. Strontium 90, because of its long half-life, high ratio of activity to mass, its gaseous byproducts, is one of the most popular isotopes for use in research on nuclear batteries. The nuclear batteries generate only a minute amount of power and probably never will compete with conventional batteries except possibly in instances where a minute and continuous power output is desired for a very long period (*51*).

However, the unique properties of these batteries may stimulate the invention of new, or redesign of existing, devices (clocks, for example) or gadgets, utilizing the following significant characteristics:

1. A source of continual voltage and current in a compact and portable size.
2. Very long life.
3. Insensitivity to extreme temperature conditions, pressure variations, or strong electric or magnetic fields.

The technology of nuclear batteries is just being developed.

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